# **MIMAC** Directional Detection of Dark Matter

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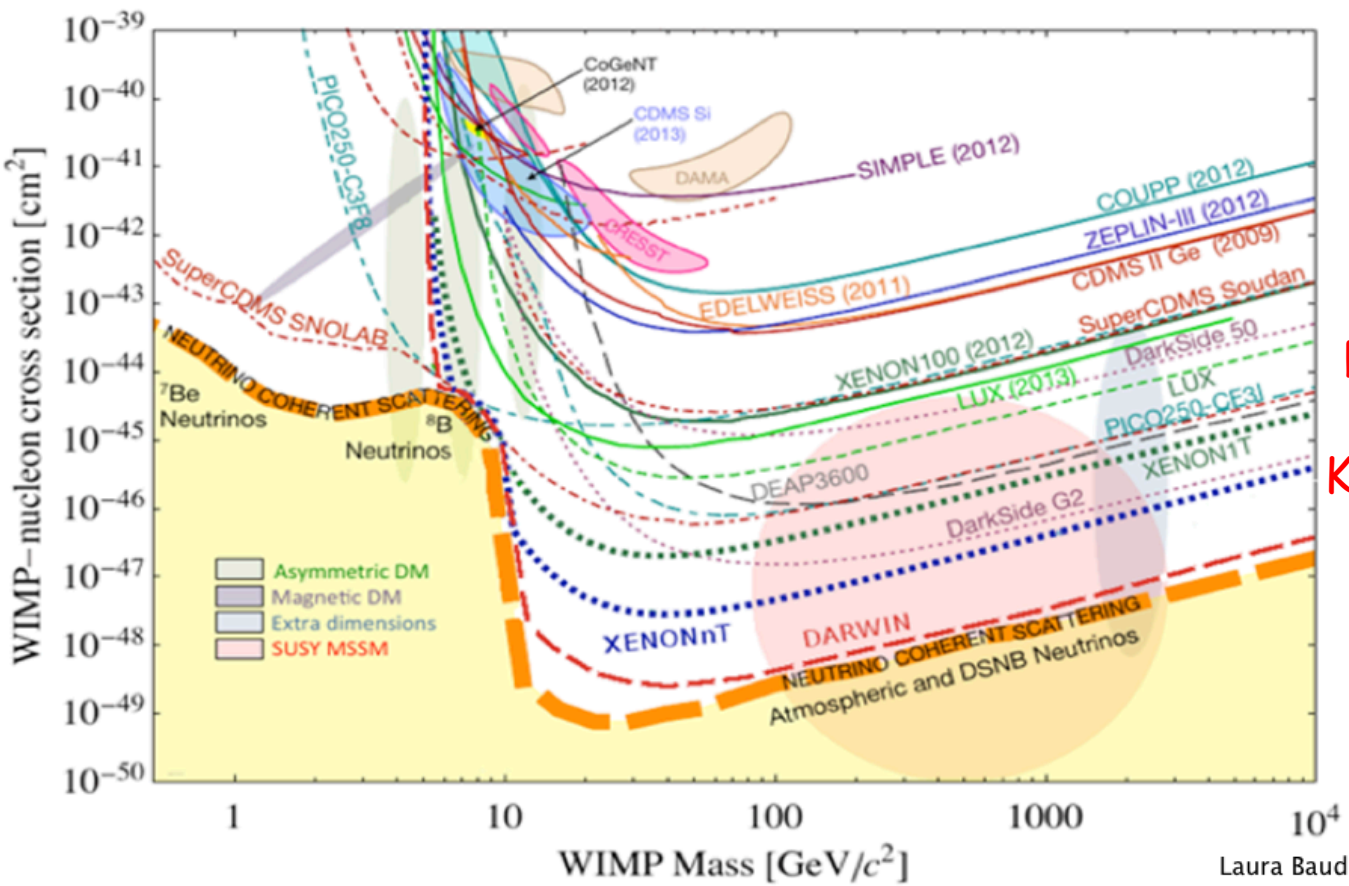
# WHY DIRECTIONAL DETECTION?

- Signature of galactic origin of any candidate signal
- Going beyond neutrino floor



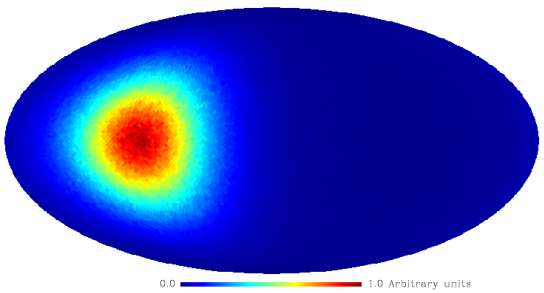

Laura Baudis (2014)

All experiments not in competition but **complementary!**

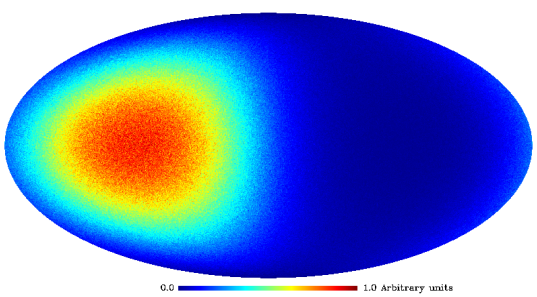
Key: Confirmation of DM Signal !

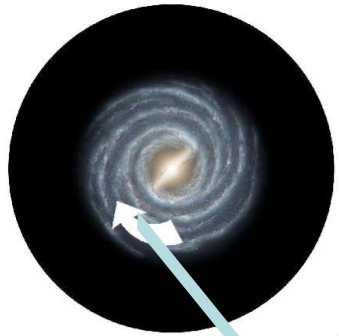
# Directional Detection: Principle

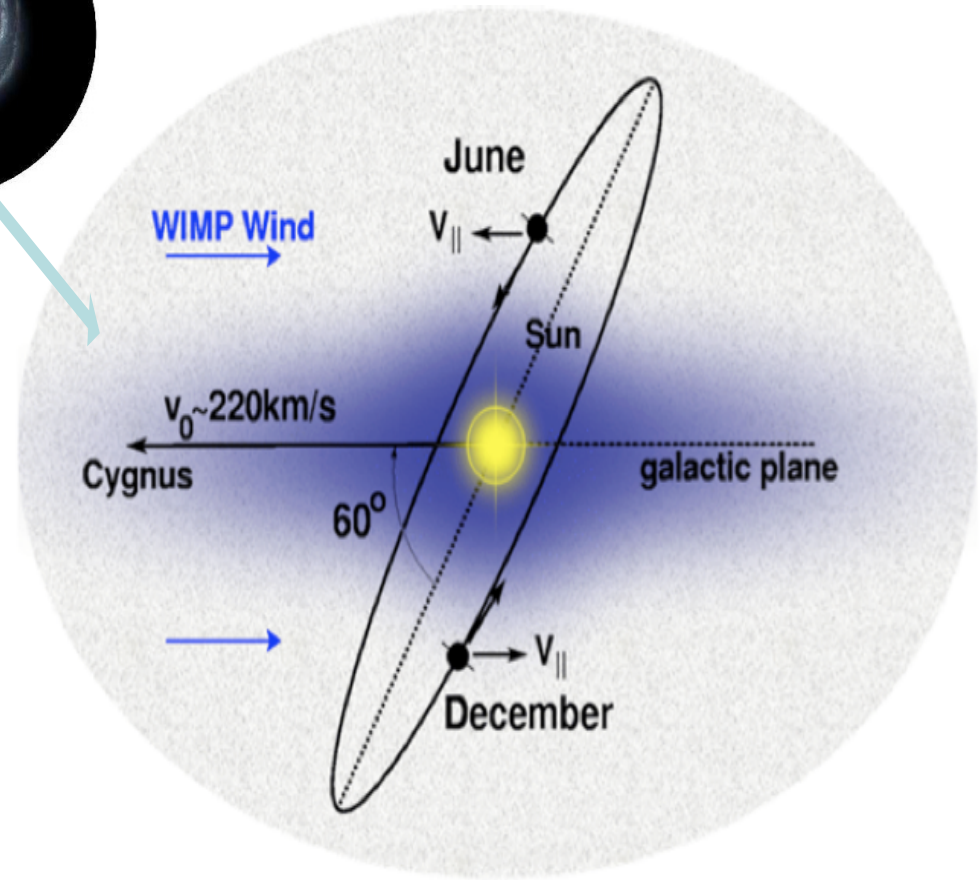
*Cygnus Constellation*
(l = 90, b = 0° )




*After collision*



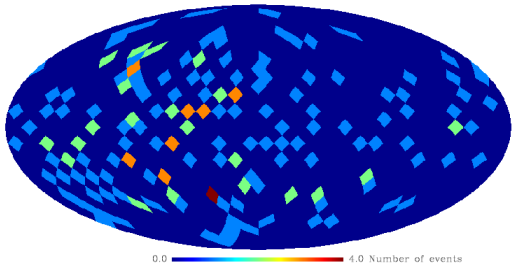



(Almost) the only signature able to correlate events in a detector to the galactic halo!

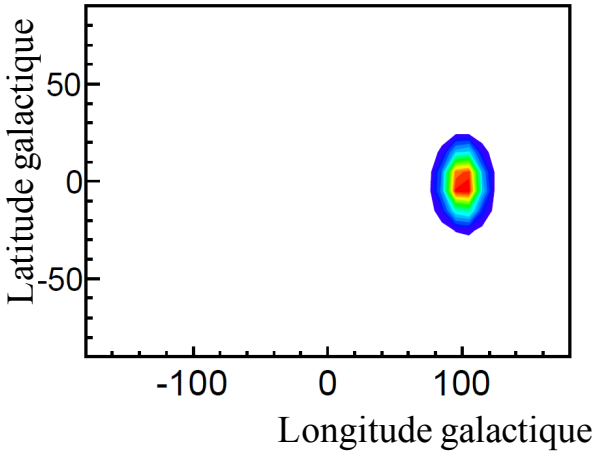
# Angular Resolution Requirement: < 20°

R&D study for requirements: measurable tracks, measurable directionality, head-tail discrimination, ion/electron discrimination, $Q_F$, initial angle reconstruction, …

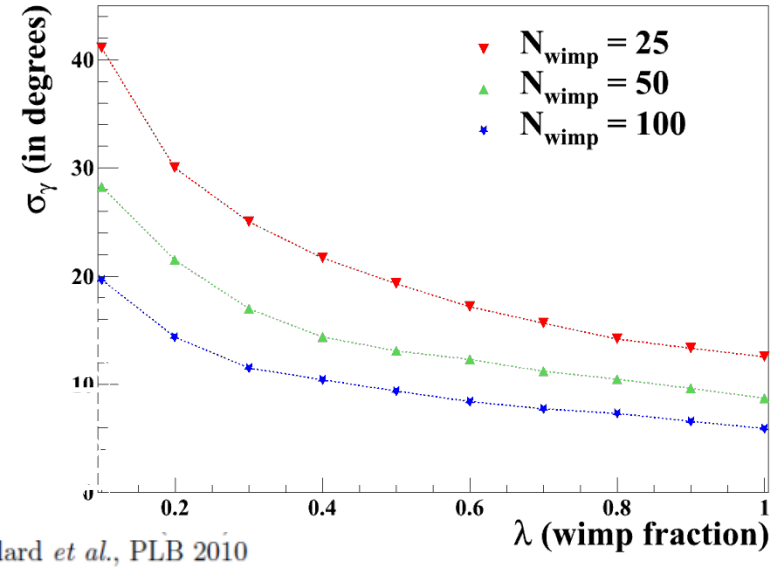
**Blind likelihood analysis in order to establish the galactic origin of the signal.**




$$\mathscr{L}(\ell, b, m_\chi, \lambda)$$




*100 WIMP + 100 BKG*




J. Billard *et al.*, PLB 2010
J. Billard *et al.*, arXiv:1110.6079

**Strong correlation possible** with the direction of the Cygnus Constellation **even with a large background contamination**

# MIMAC (MIcro-tpc MAtrix of Chambers )

**LPSC (Grenoble) : D. Santos, F.Naraghi , N. Sauzet** (CDD)

-Technical Coordination, Gas circulation and detectors : **O. Guillaudin**

- Electronics : **G. Bosson, J. Bouvier, J.L. Bouly, L.Gallin-Martel, F. Rarbi**
- Data Acquisition: **T. Descombes**
- Mechanical Structure : **J. Giraud**
- COMIMAC (quenching) **:** **J-F. Muraz**

**IRFU (Saclay): P. Colas, I. Giomataris**

**CCPM (Marseille): C. Tao, J. Busto**

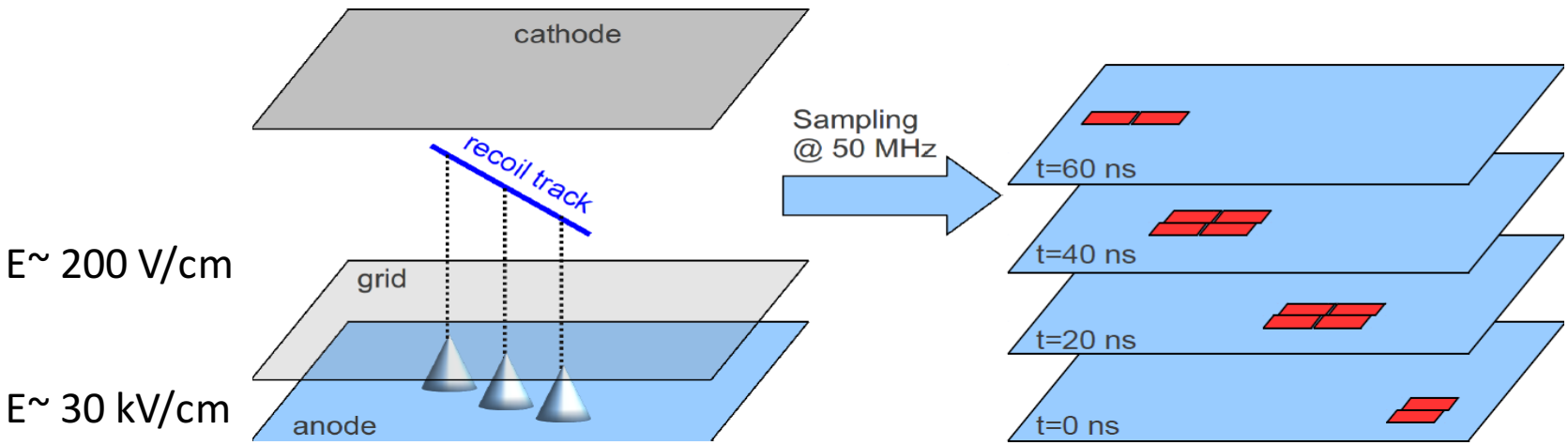
**Tsinghua University (Beijing-China): C. Tao, I. Moric (post-doc), Y. Tao (Ph.D)**

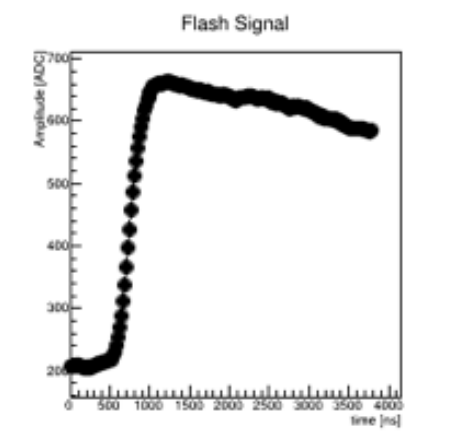
Prototype hosted in **IHEP (Beijing-China)**: **ZhiminWang , Changgen Yang**

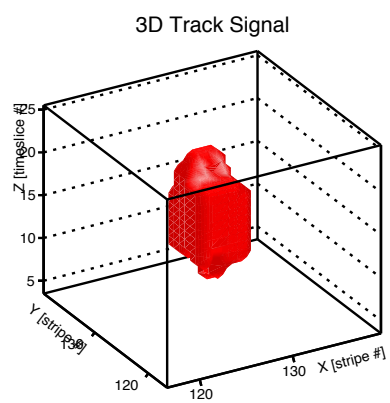
Neutron facility (AMANDE) :

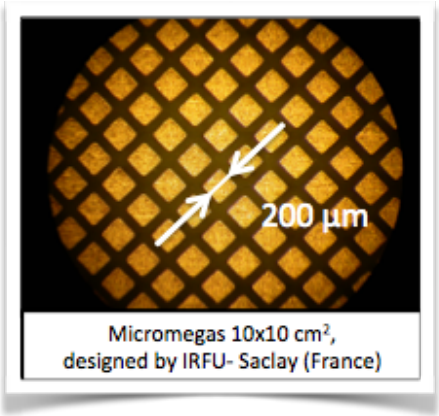
**IRSN (Cadarache): V. Lacoste, B. Tampon (Ph. D.)**

# MIMAC: Detection Strategy

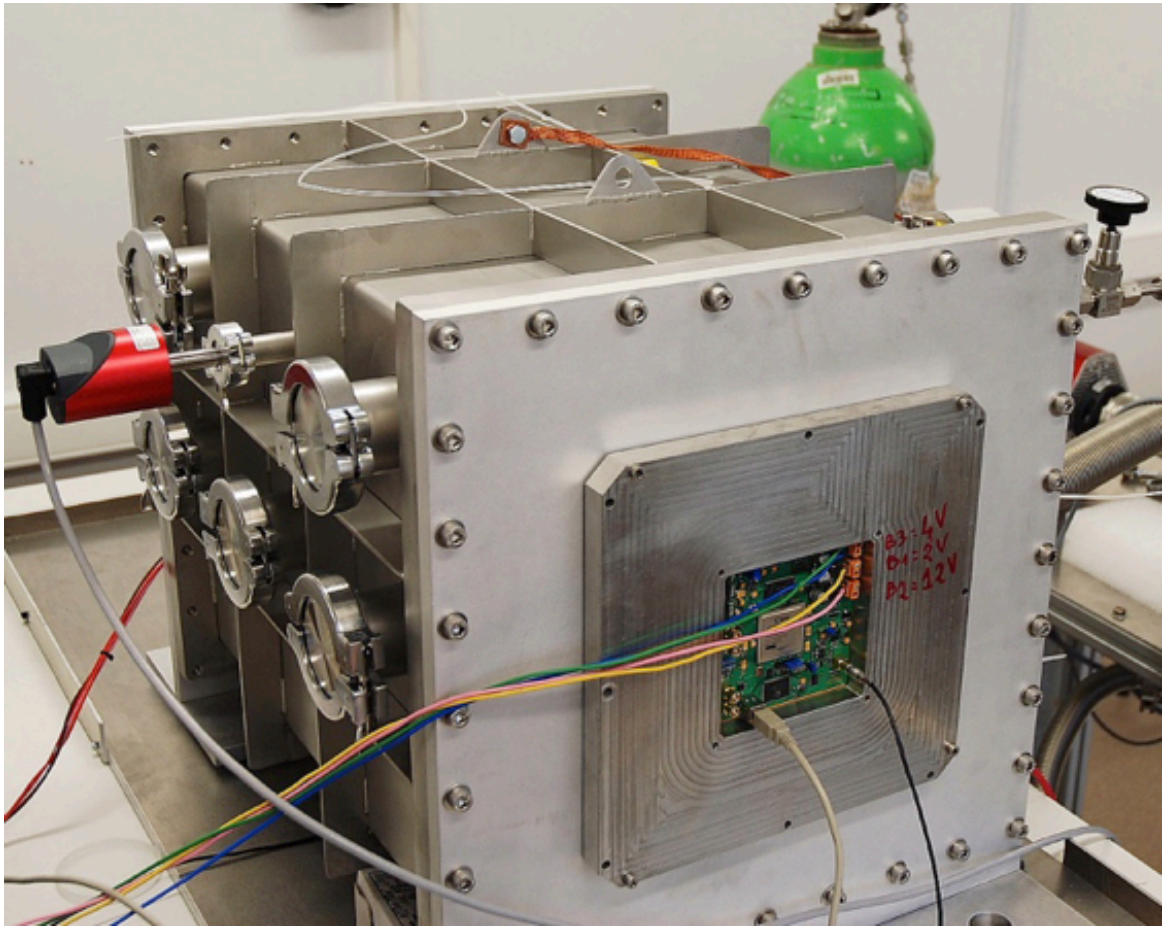


# MIMAC Bi-Chamber Module

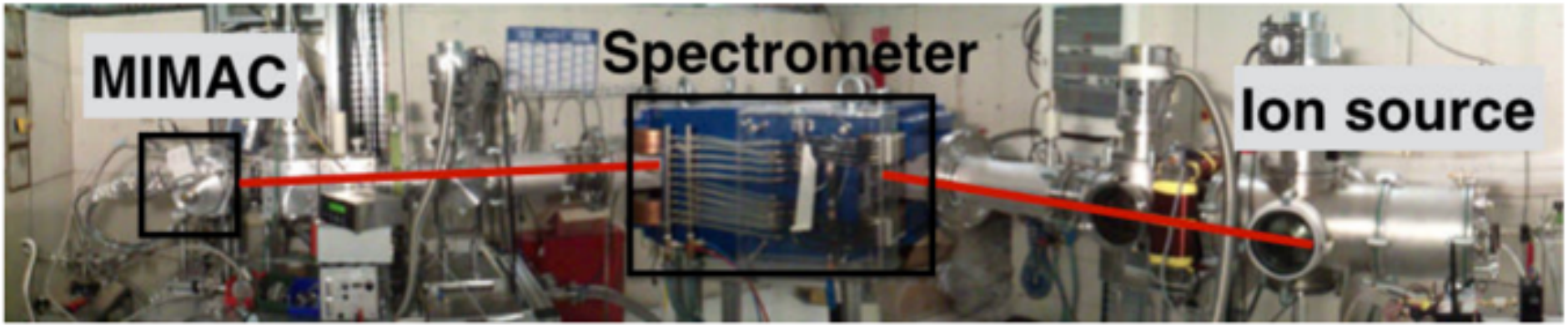


Bi-chamber module
2 x (10.8 x 10.8 x 25 $cm^3$)

- **Energy Measurement**
- **3D Track Reconstruction**
- **Target Can Be changed flexibly**

# Ion Beam

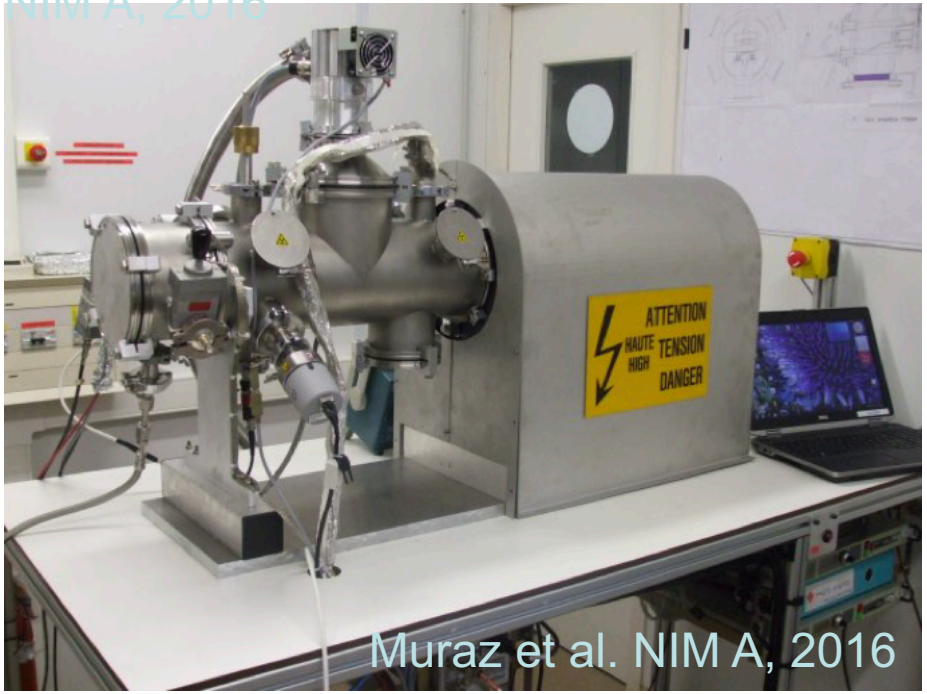
**LHI beam line**




Muraz et al. NIM A, 2016

**COMIMAC – A Portable Quenching Facility**

**Target: $^{19}F$ (but flexible to change)**



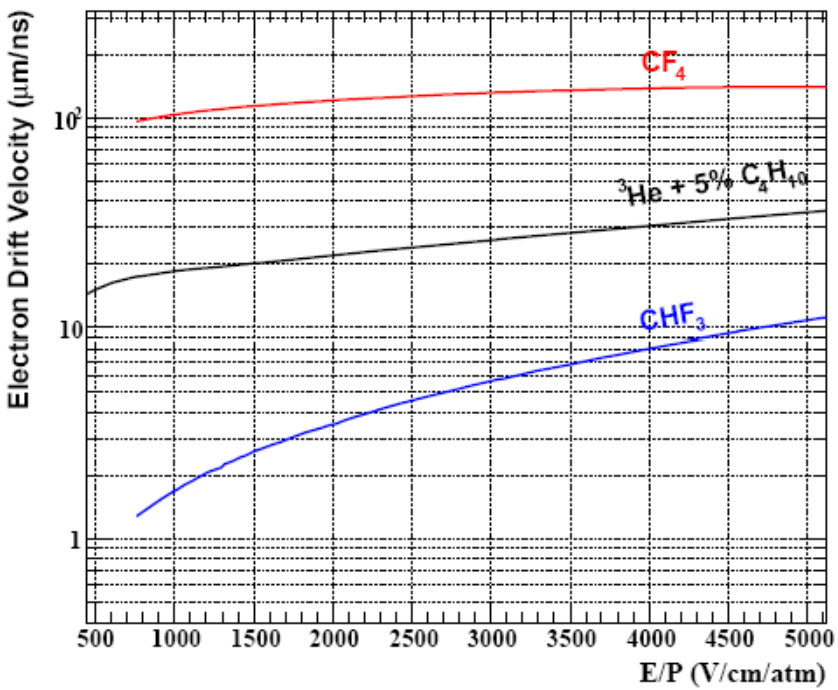

Muraz et al. NIM A, 2016

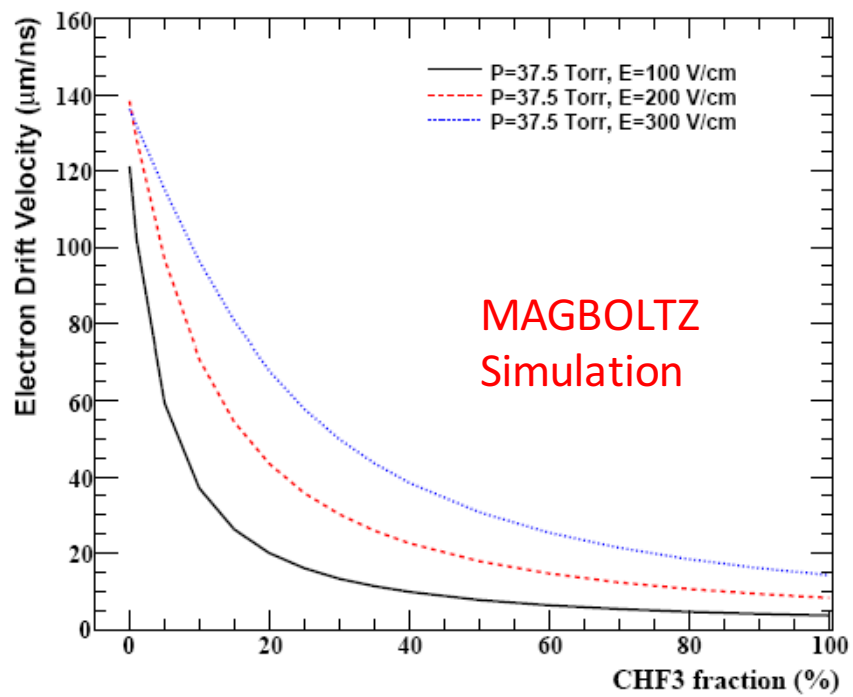
# Special Gas Mixture – MIMAC gas

- Mixture component:

  -- 70% $CF_4$ + 28% $CHF_3$ + 2% $iC_4H_{10}$

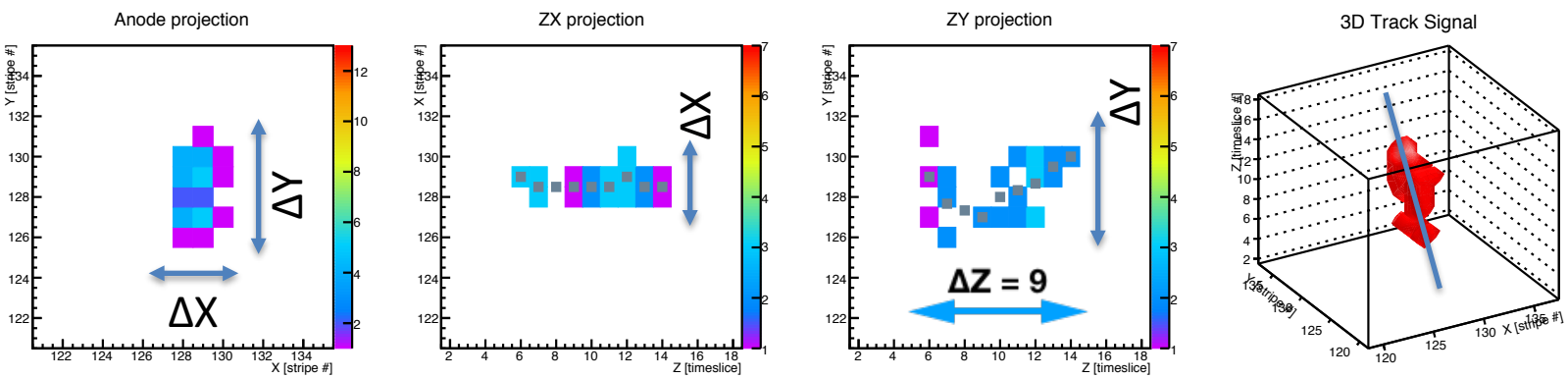
  -- reduce the electron drift velocity as well as keeping tracks long enough
- Operating at low pressure: 50 mbar



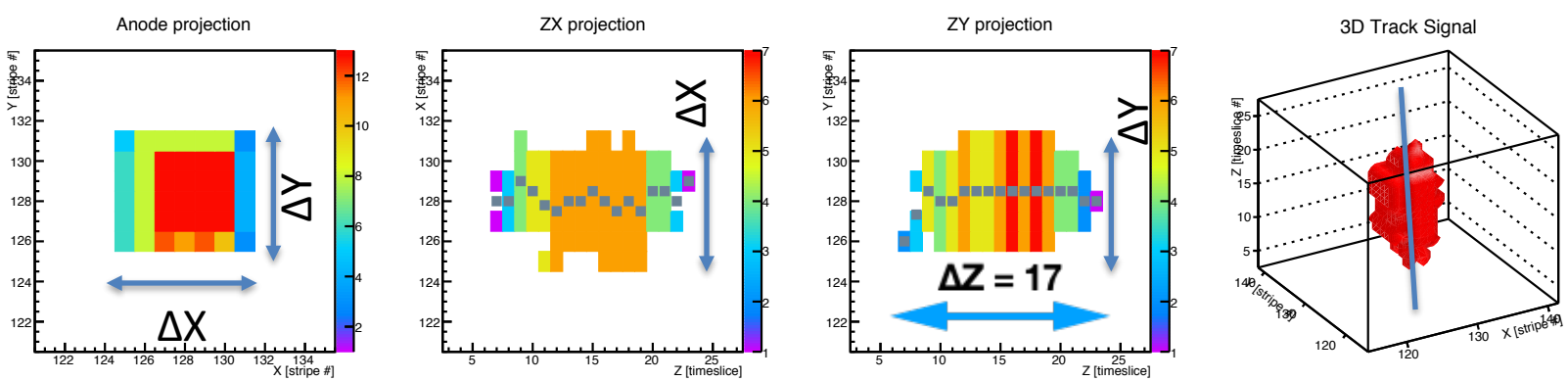



# MIMAC: The only detector that has 3D-reconstructed keV tracks.

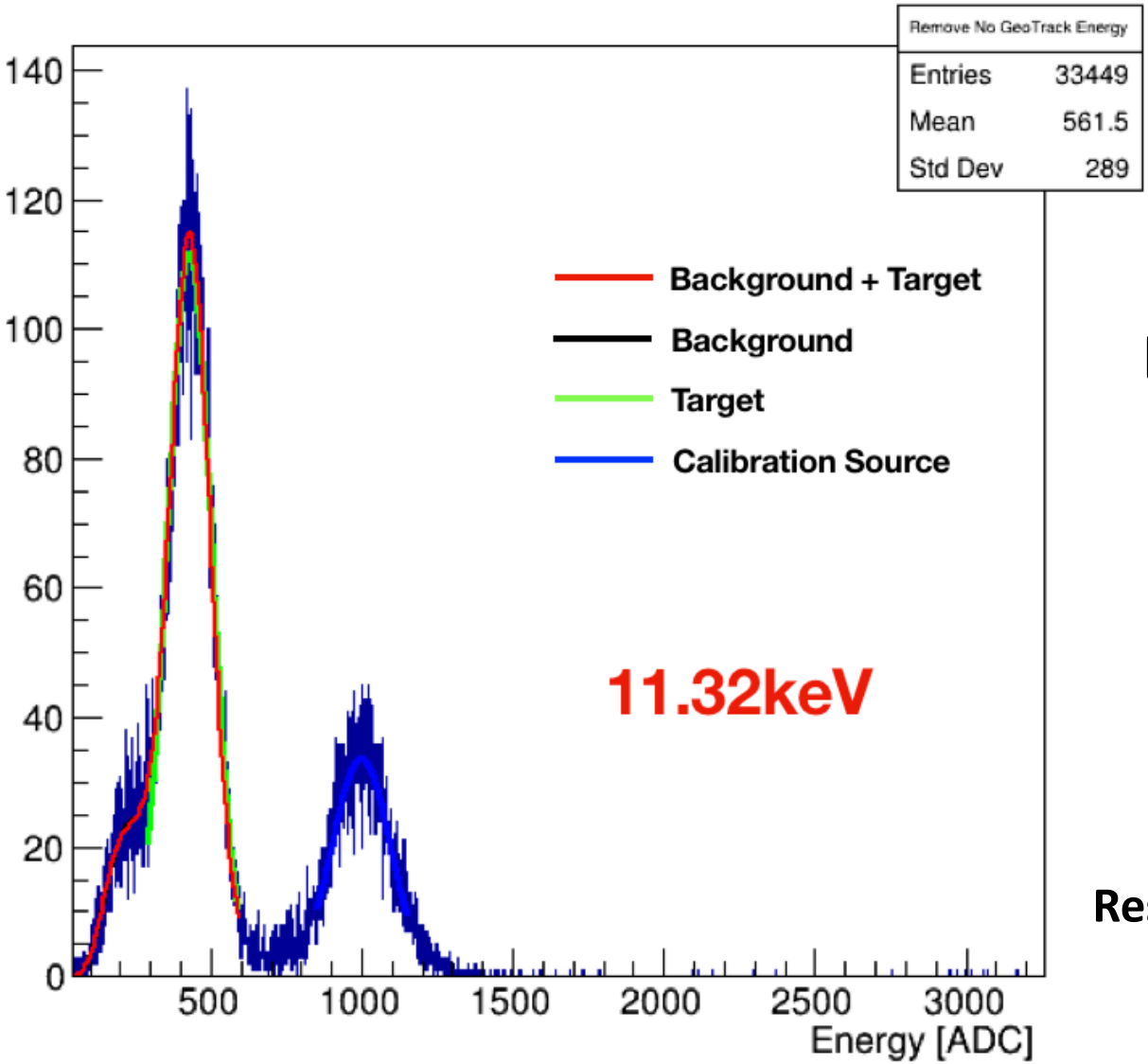
## Fluorine 6.3 keV (~2 keVee)




## Fluorine 26.3 keV (~9 keVee)



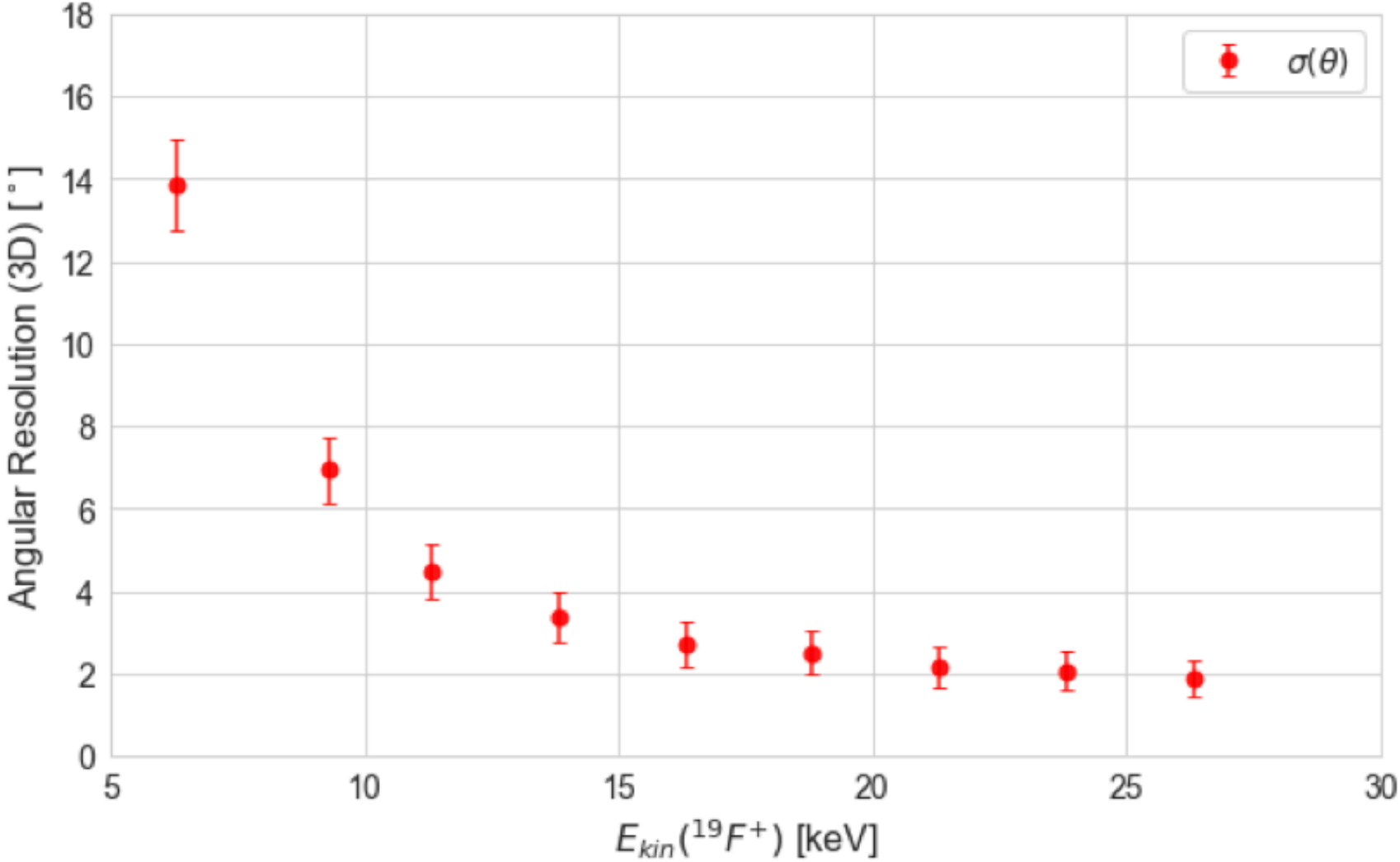
# Energy Resolution < 15% (FWHM)




**Energy Spectrum of a 11.32 keV F ion run as an example**

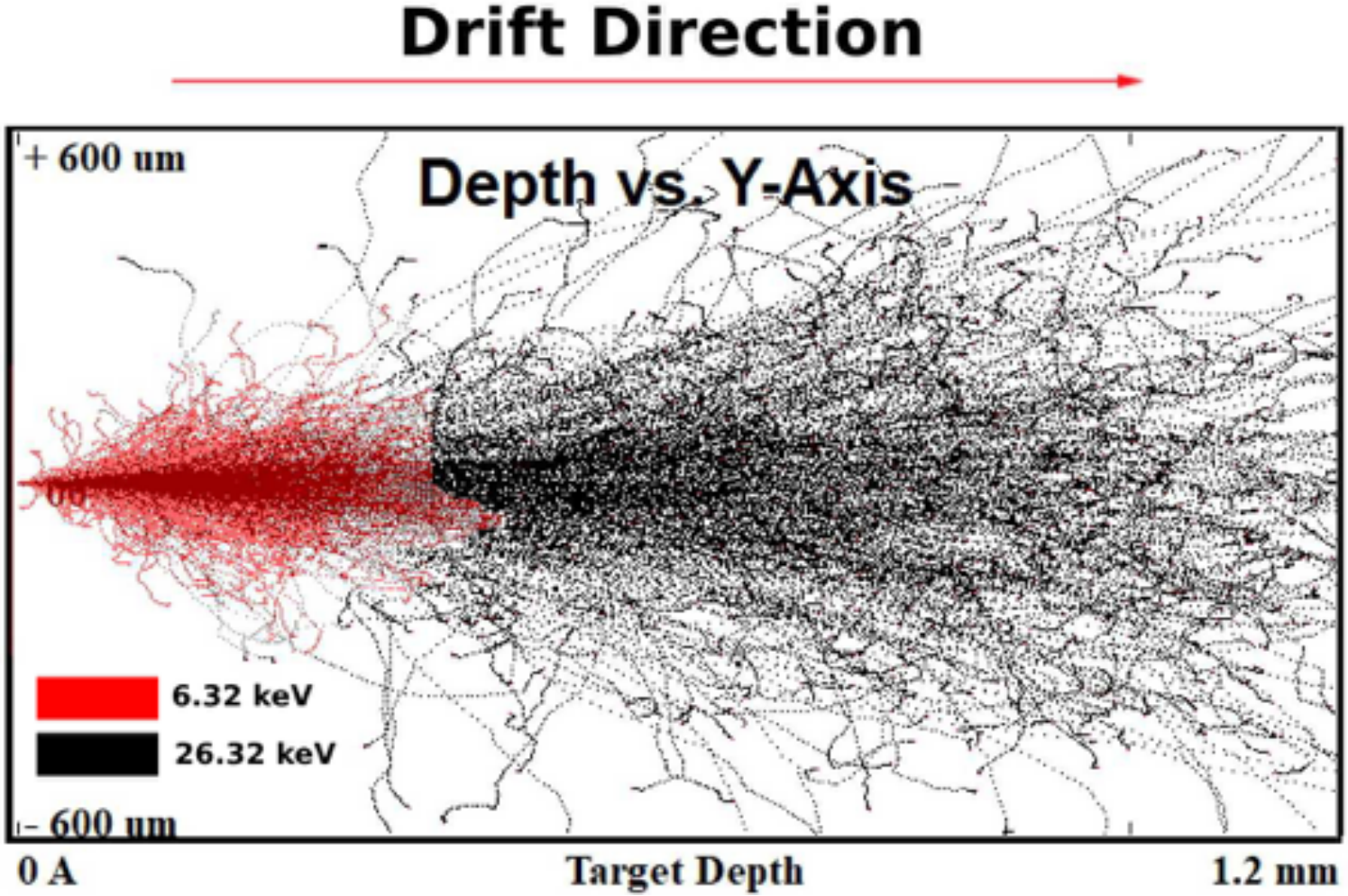
**Resolution: < 15% (FWHM)**

# Angular Resolution: better than required 20 degree




Y. Tao *et al.*, arXiv: 1903.02159

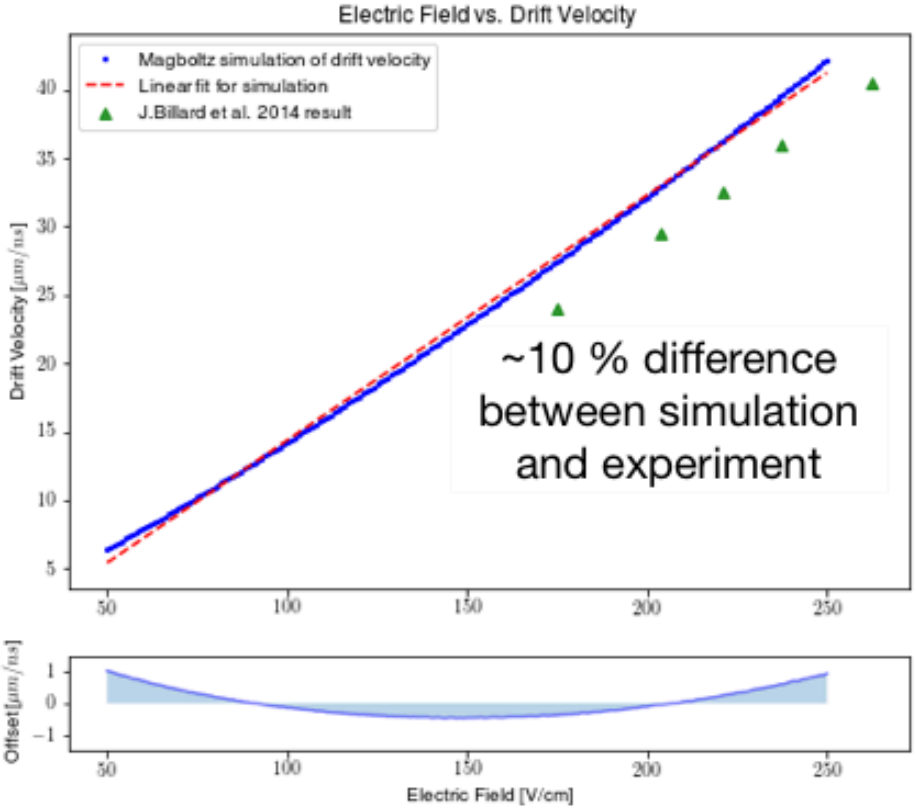
# SRIM Simulation Results

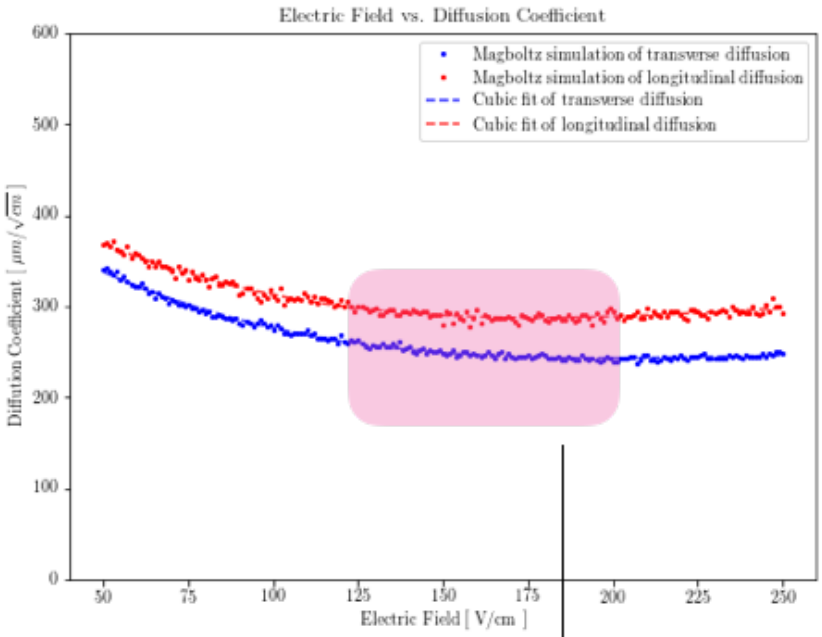



**SRIM (Stopping and Range of Ions in Matter)**

- Key Points: No external fields applied

# Drift Velocity and Diffusion Coefficient Results from MAGBOLTZ Simulation

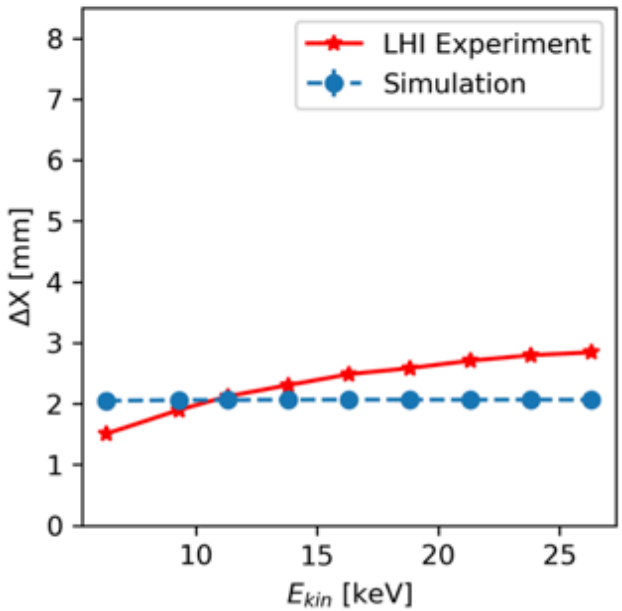


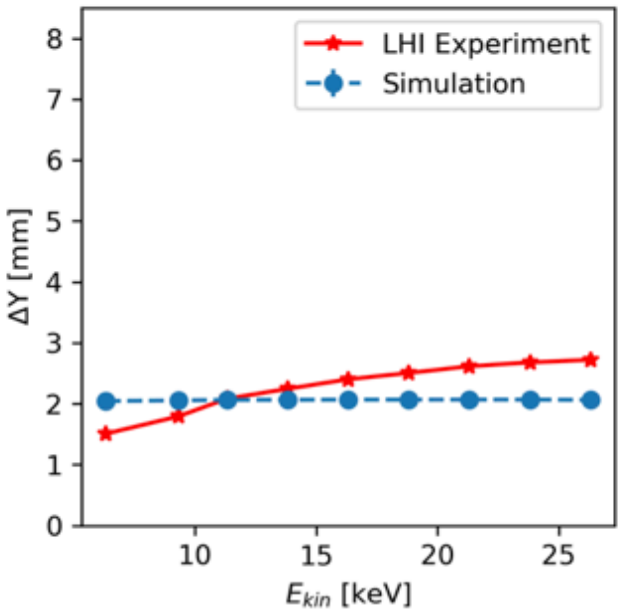

**Conclusion:** In the experimental range, simulation only give a few difference between transversal and longitudinal diffusion impact (But this difference will be enhanced if the drift distance is large enough)

# Comparison with Simulation (SRIM + MAGBOLTZ)

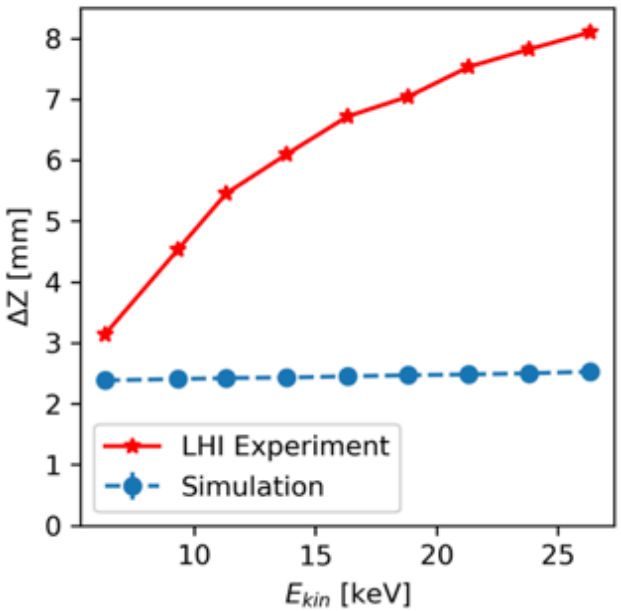
Width X




Width Y




Depth Z

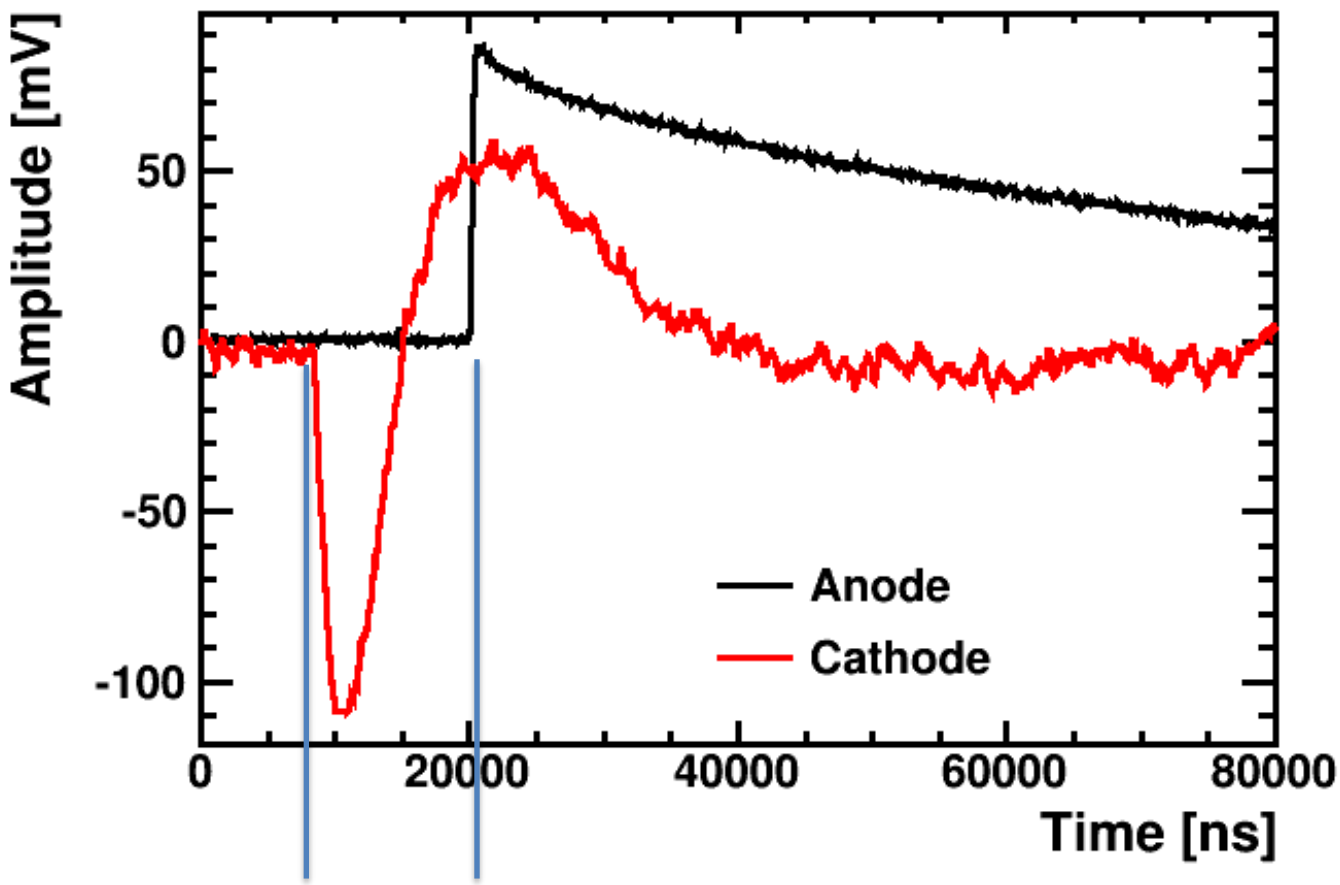



Large discrepancy !!

Molecular effect ?

# RECENT PROGRESS

# Cathode Signal Measurement

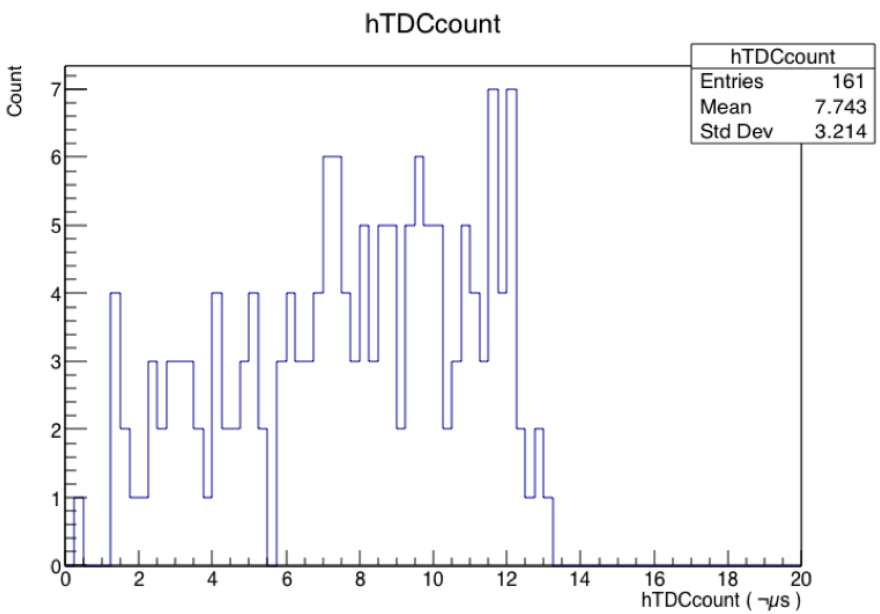



Time difference

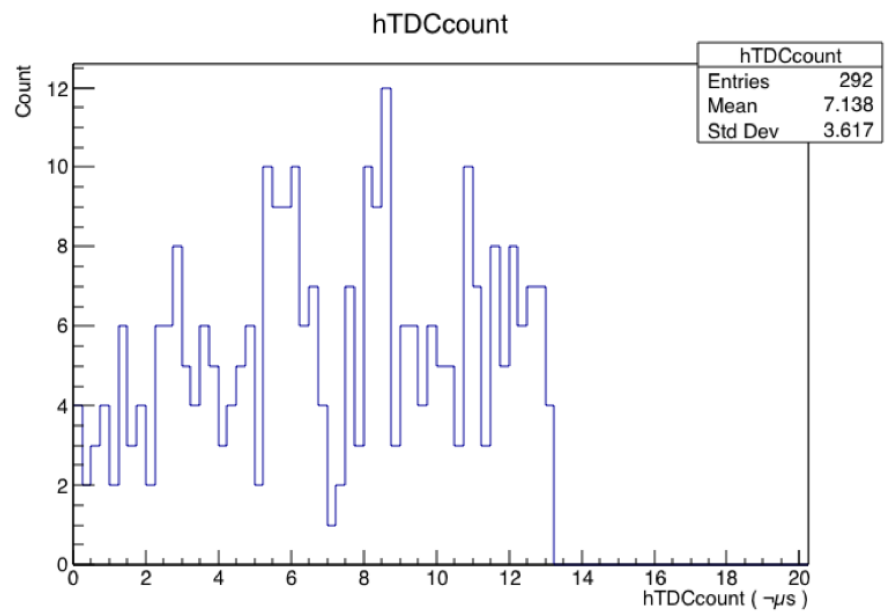
# First Cathode Signals time distribution from the MIMAC bichamber background

(O. Guillaudin, D.S. et al. October 2018)

Chamber 1

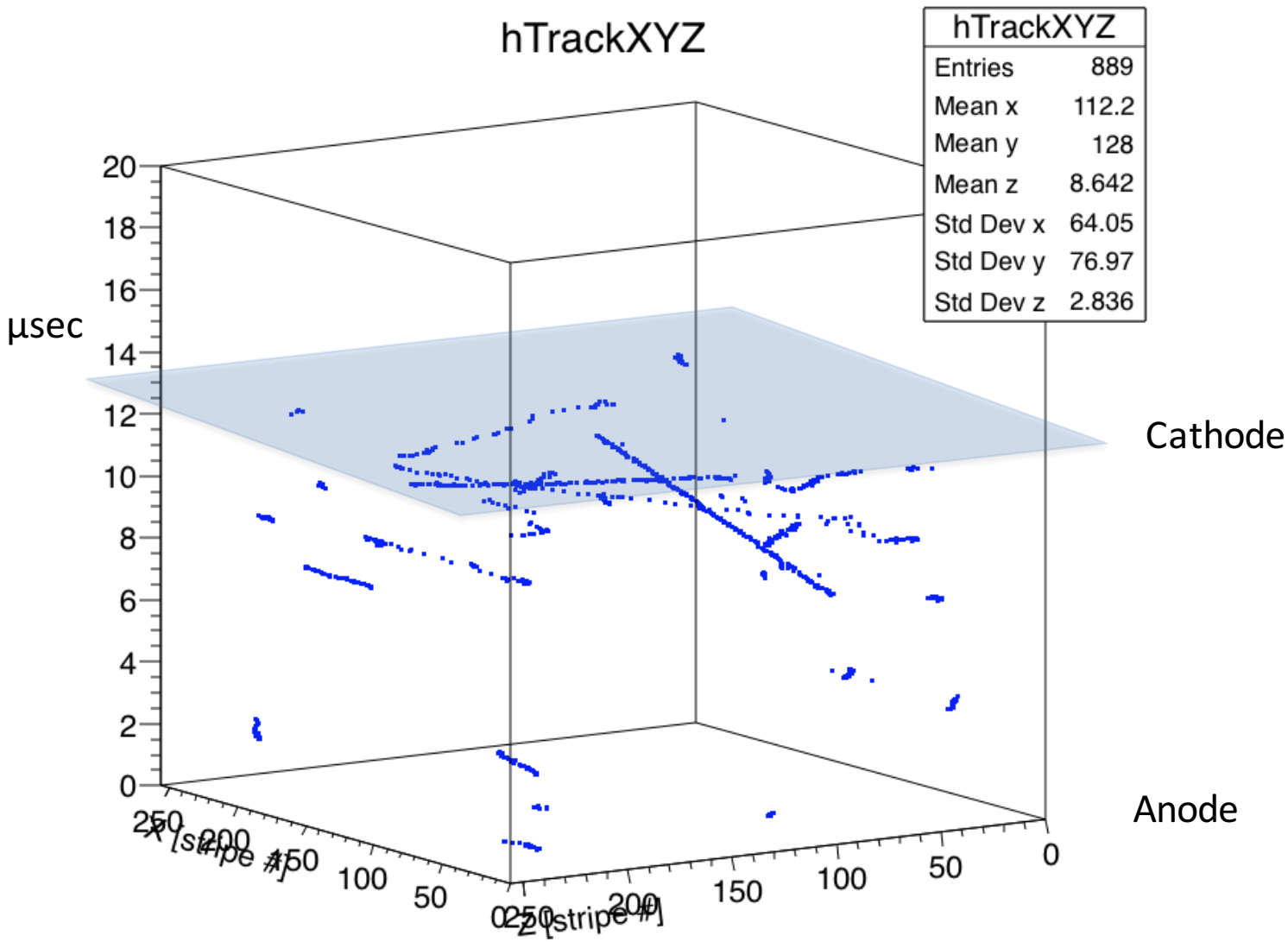



Chamber 2



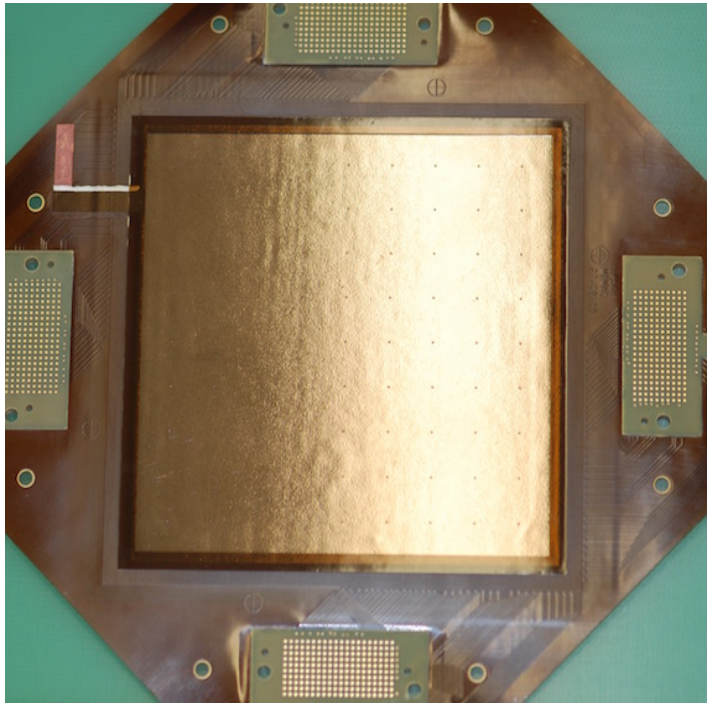

Measuring the time between the “event production” and the avalanche signal !!
Covering the 26 cm drift distance (13 us x 20 um/ns) !!

# 3D event-localization in MIMAC

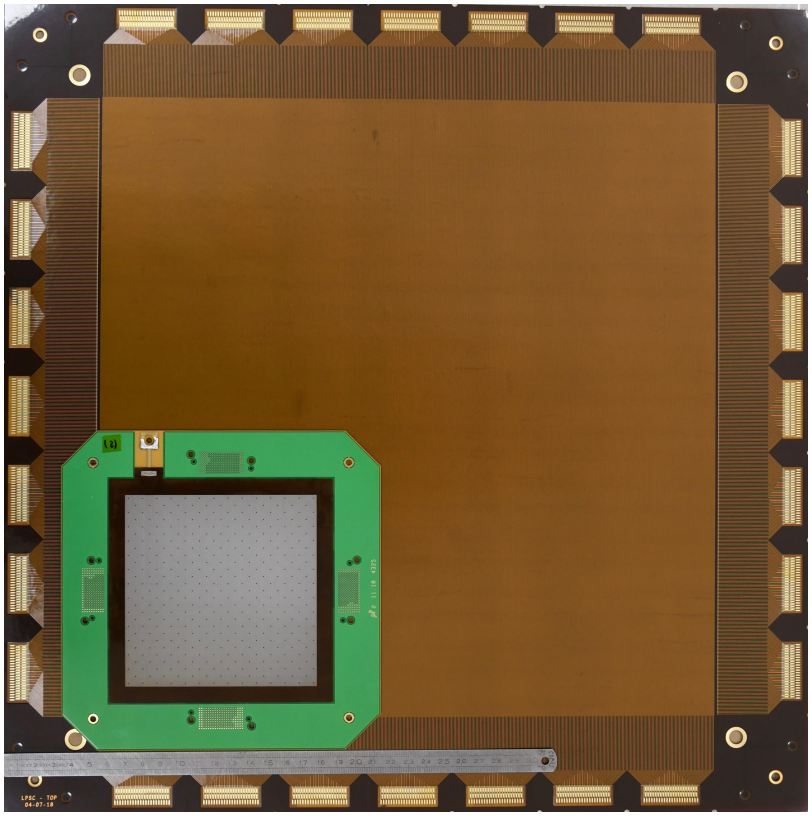


# New MIMAC low background detector

（new 10 cm × 10 cm）



（35 cm × 35 cm） under design



# MIMAC 1m$^3$ in preparation

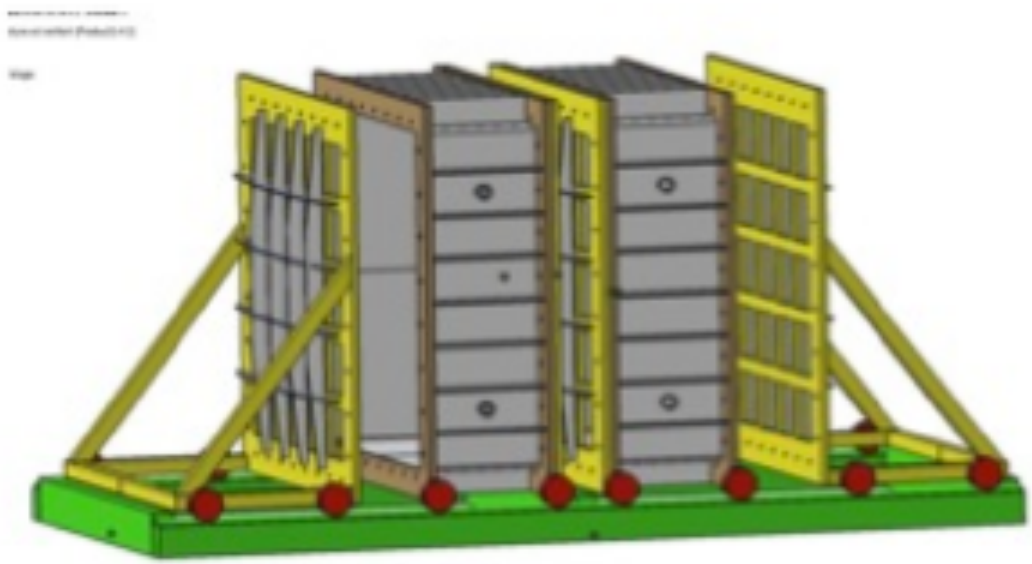
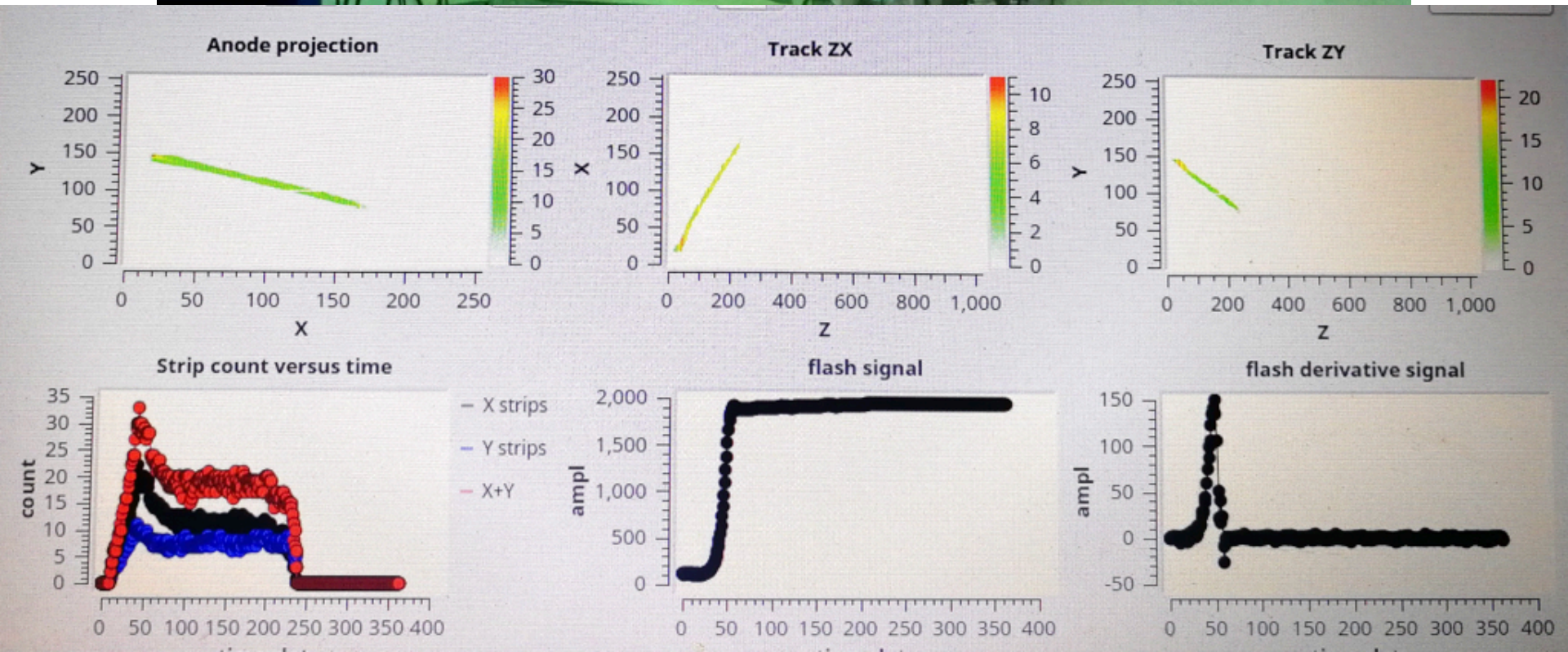


**Figure 5.** The preliminary mechanical design of the demonstrator of MIMAC -1 m$^3$ .

**Installation in 2019-2020 in LSM**

# MIMAC Chamber in Beijing (IHEP)



# Plans for the Future

- Data Analysis from monoenergetic neutrons produced at Amande facility in Cadarache (France).
- Data Analysis from 5 years in LSM (Modane Underground Laboratory) with the previous prototype.
- Improve electron-nuclear recoil discrimination.
- MIMAC 1 $m^3$ in LSM will be installed as soon as the $35 \times 35$ $cm^2$ bi-chamber module is working.

# Summary

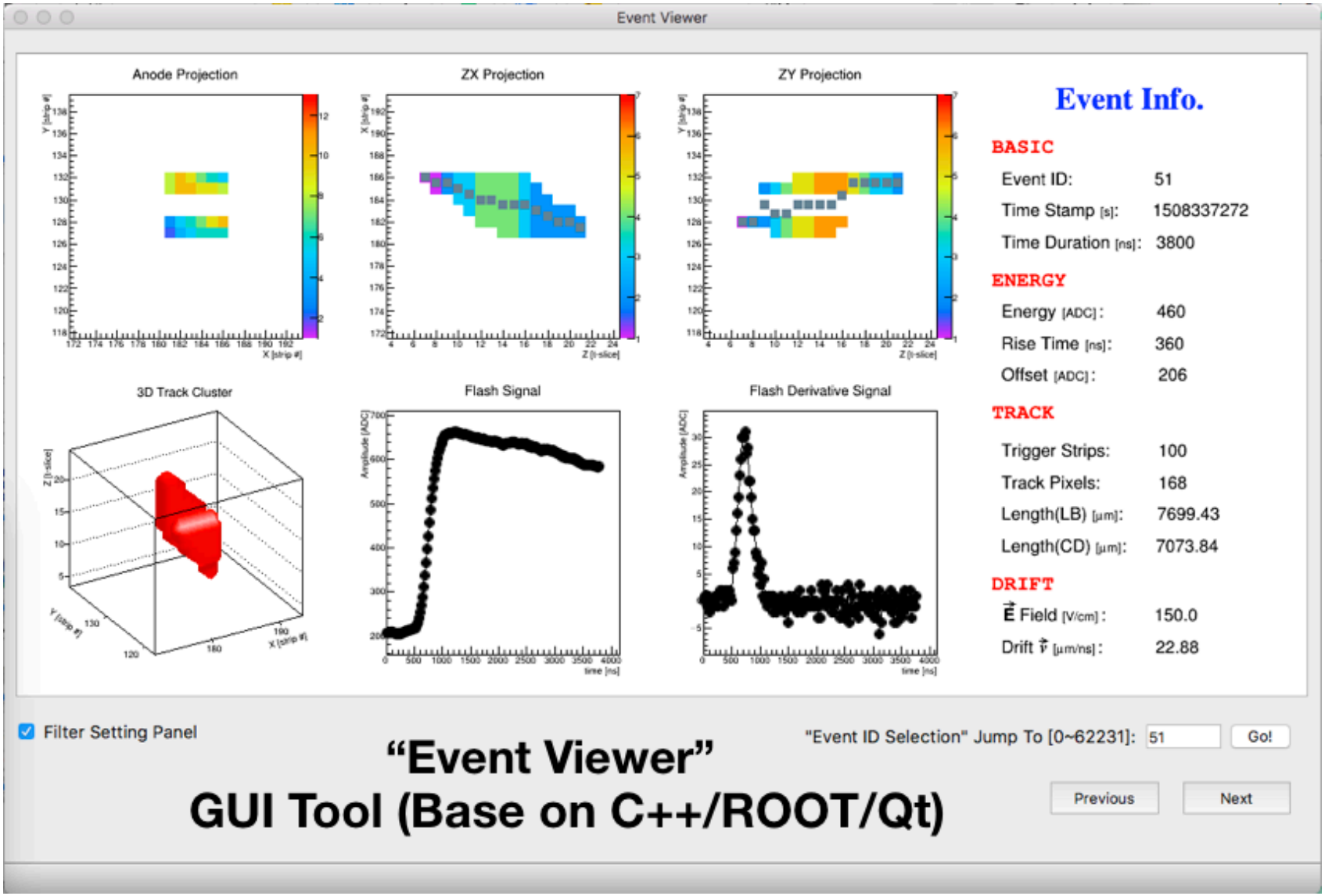
- Directional detection is an essential counter part for the major detection projects that are mainly focus on energy channel.
- A new directional detector of nuclear recoils at low energies (E > 100 eV) has been developed giving a lot of flexibility on targets, pressure, energy range… —> MIMAC!
- Angular resolution and directional studies of 3D tracks have been performed experimentally with LHI facility, showing a promising result for future detection, while large discrepancies with respect to simulations!
- Cathode measurement allows us to fiducialize Z much better.
- The 1 $m^3$ will be the validation of a new generation of a large DM high definition detector including directionality (a needed signature for DM discovery)

Thanks for your attention!

# Backup Slides

# Event Display

# Event Display — GUI Tool

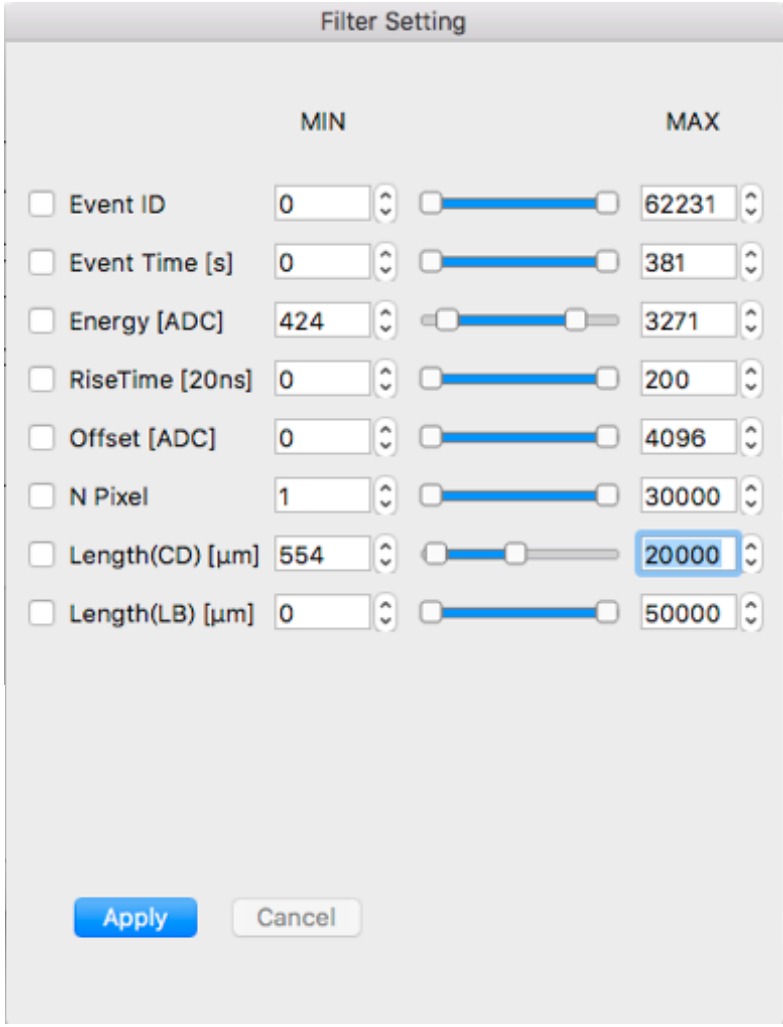



**"Event Viewer"**
**GUI Tool (Base on C++/ROOT/Qt)**

# Event Display — GUI Tool

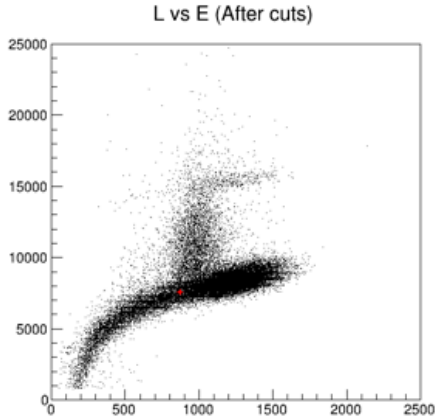
## Features:

1. Cross-platform
2. Offline event display
3. Fully integrated with MIMAC data analysis (fixed structured ROOT files)
4. Adjustable cut-off on key physical observables (real-time simple event filter)
5. Multiple information presented
6. Different mode choices
7. Support for ID selection (after complicated event filters)



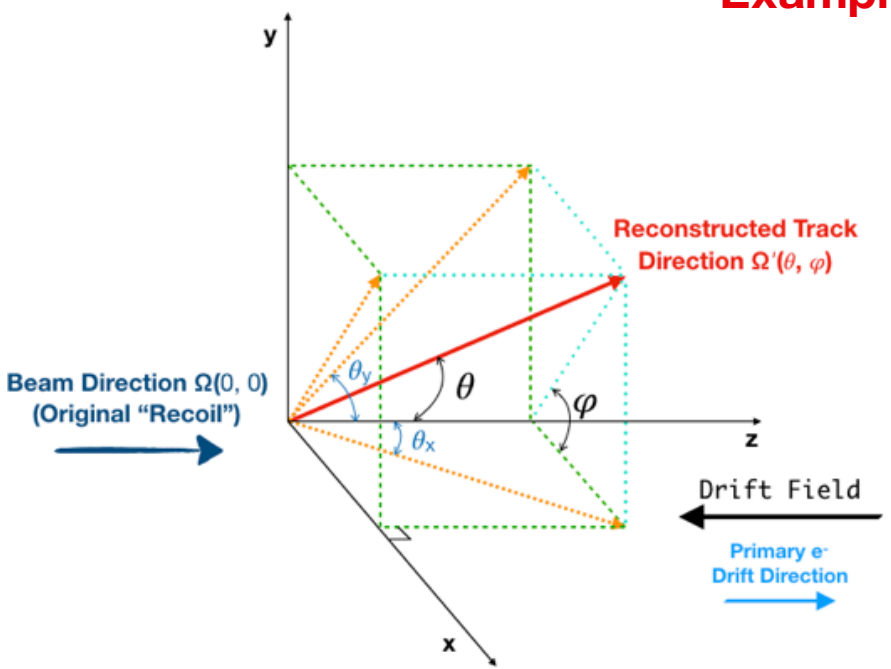

Future Plan:

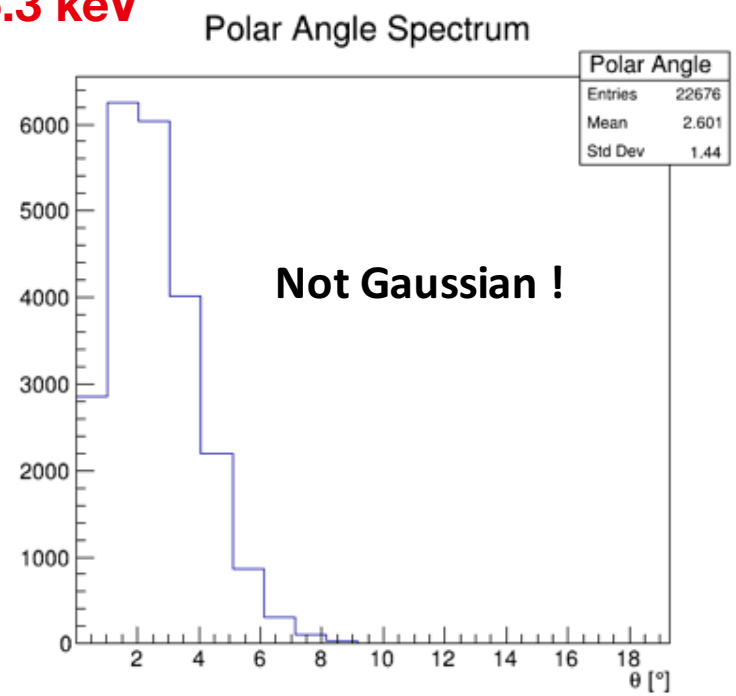
- Multi-threading
- Yet to be developed and improved…

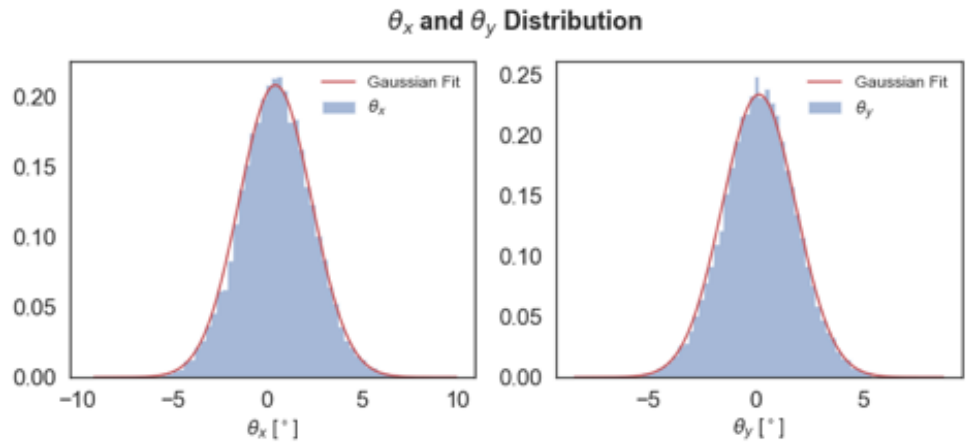


# Direction Reconstruction

**Example: 26.3 keV**




**3D polar angle: Not Gaussian**
**2D projection: Nice Gaussian**

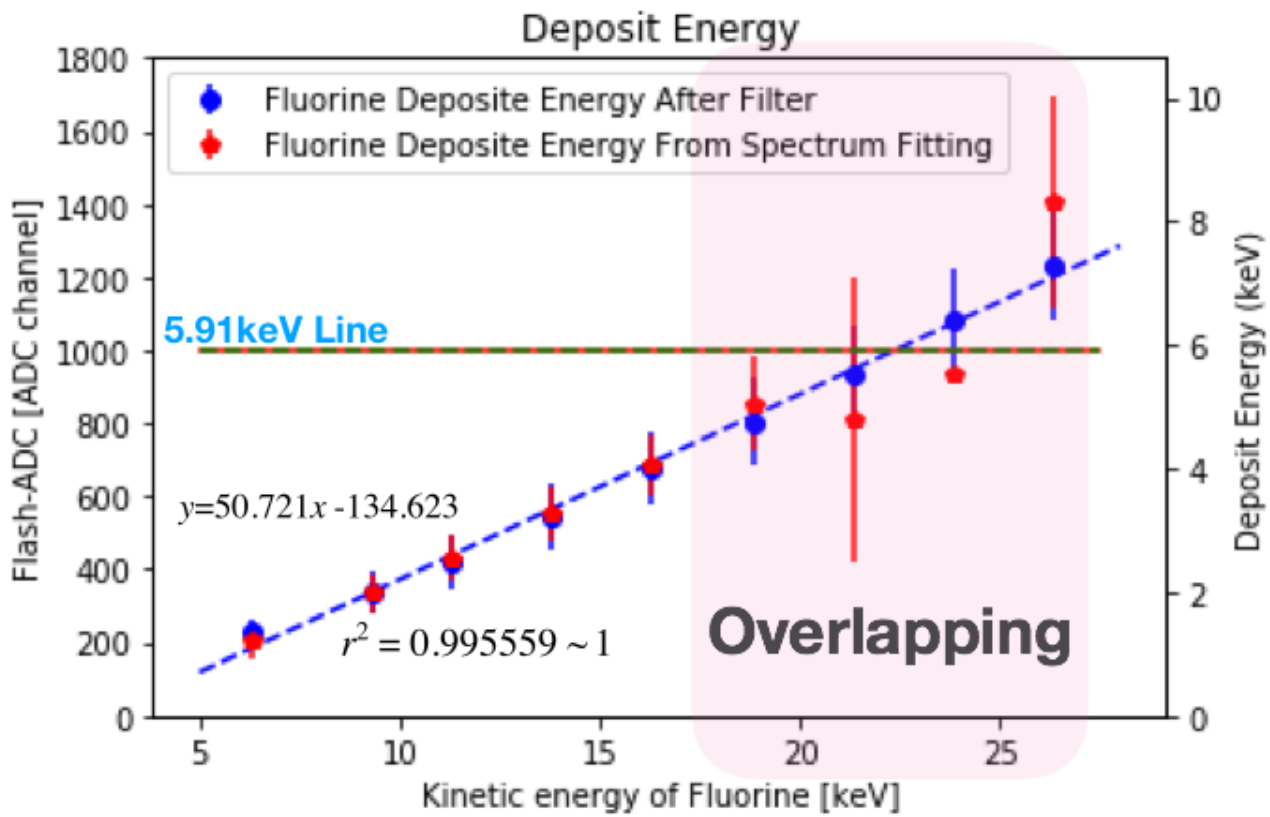
# Energy Measurement

If 0 channel in ADC is equivalence or very close to 0 in deposit energy. The Quenching Factor (IQF) is:

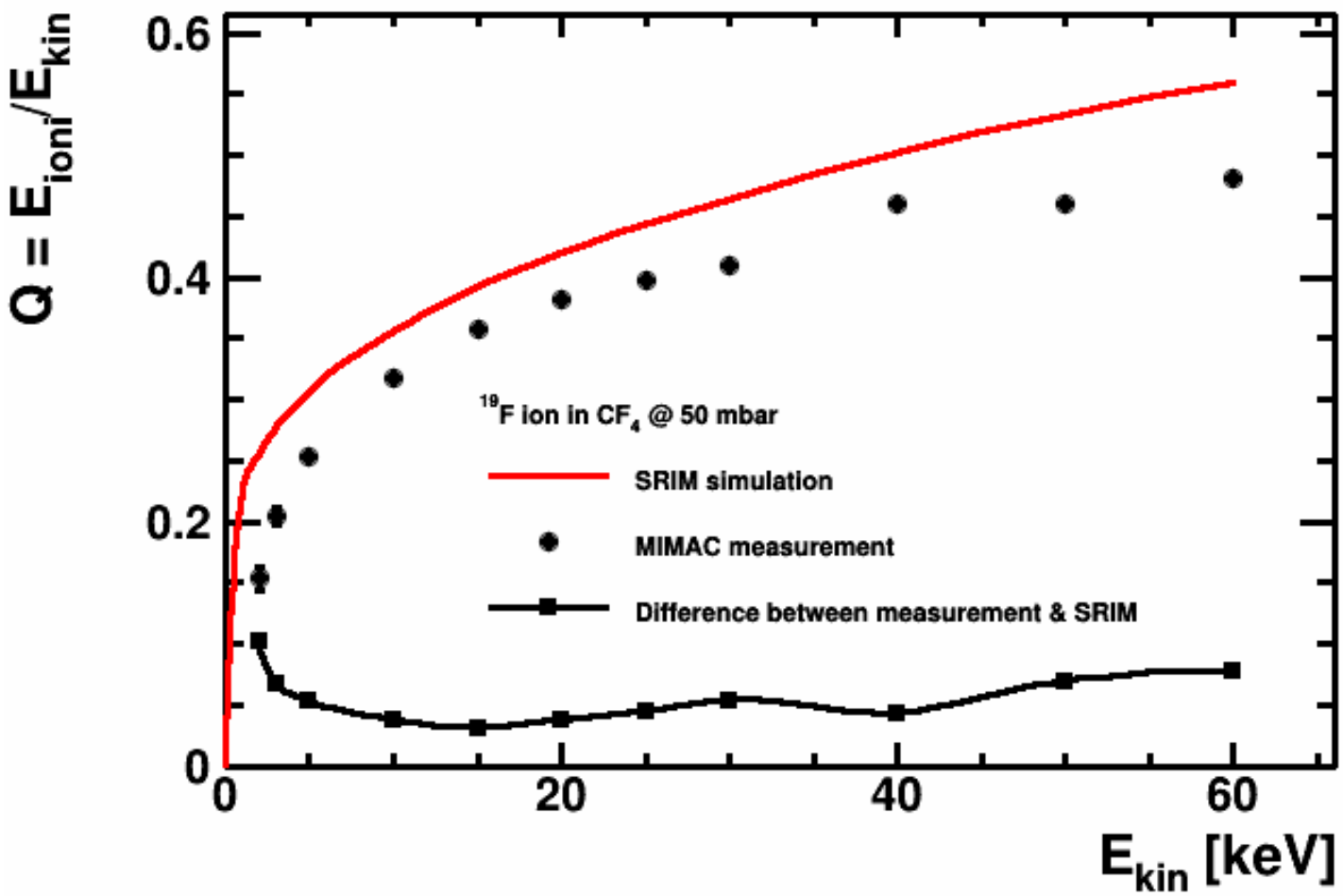
$$\frac{5.91[\mathrm{keV}]}{1000[\mathrm{ADC}]} \times 50.721[\mathrm{ADC/keV}]$$
$$= 0.299761$$
$$\simeq \underline{0.3}$$

- **In consistence with what we expected.**

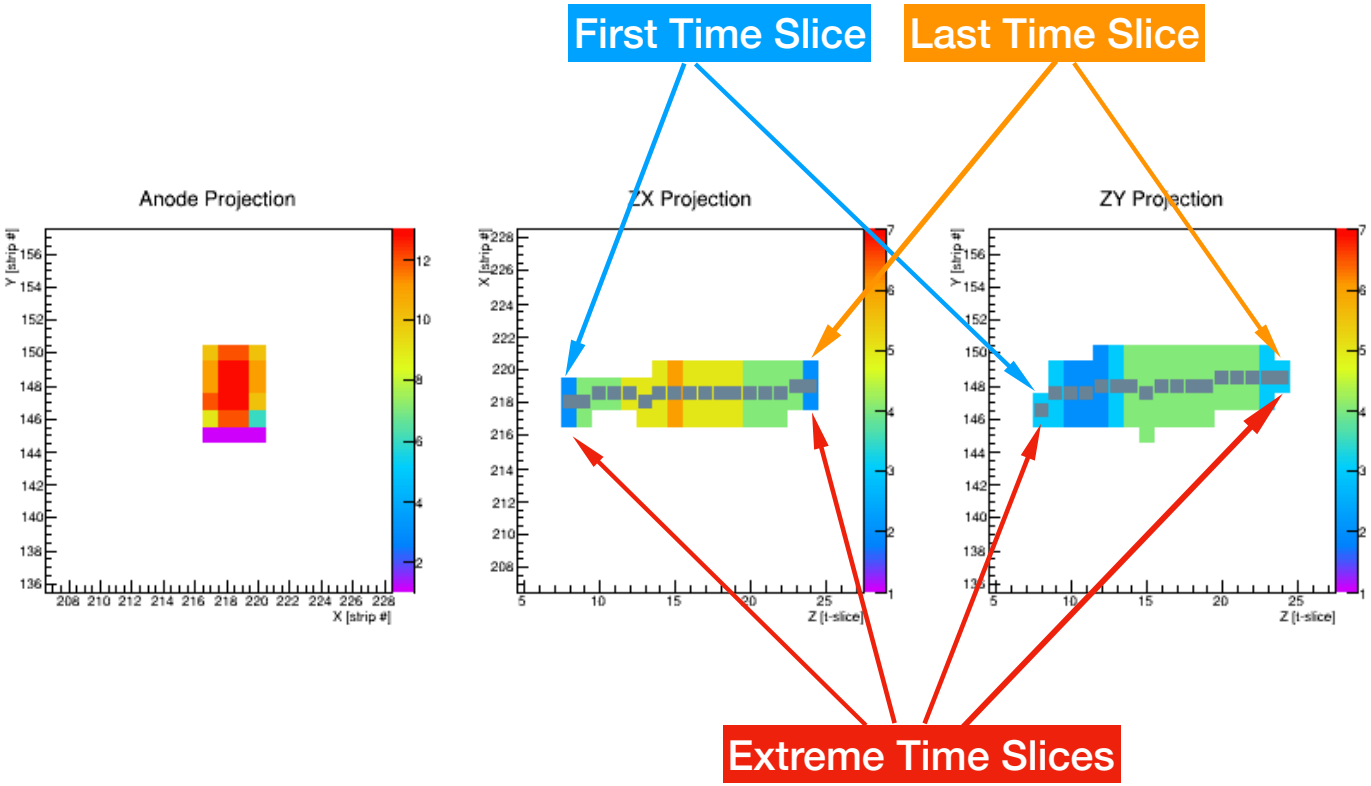
(Two calibration source (only $^{55}$Fe for now) or more, the quenching factor value will be more correct to determine.)



# Quenching Factor: Measurement and Simulation



# Track Example

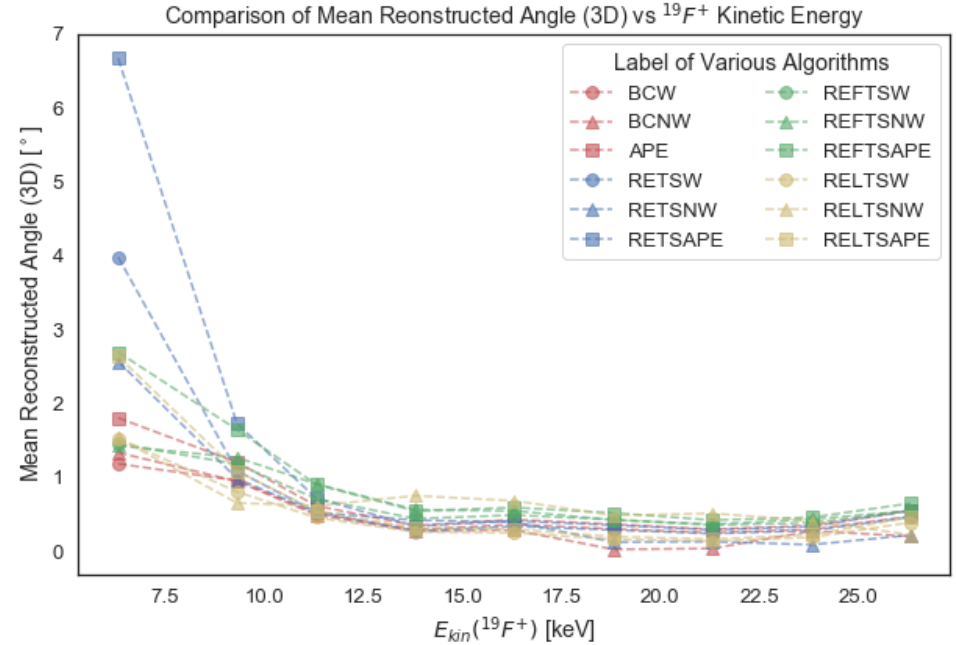


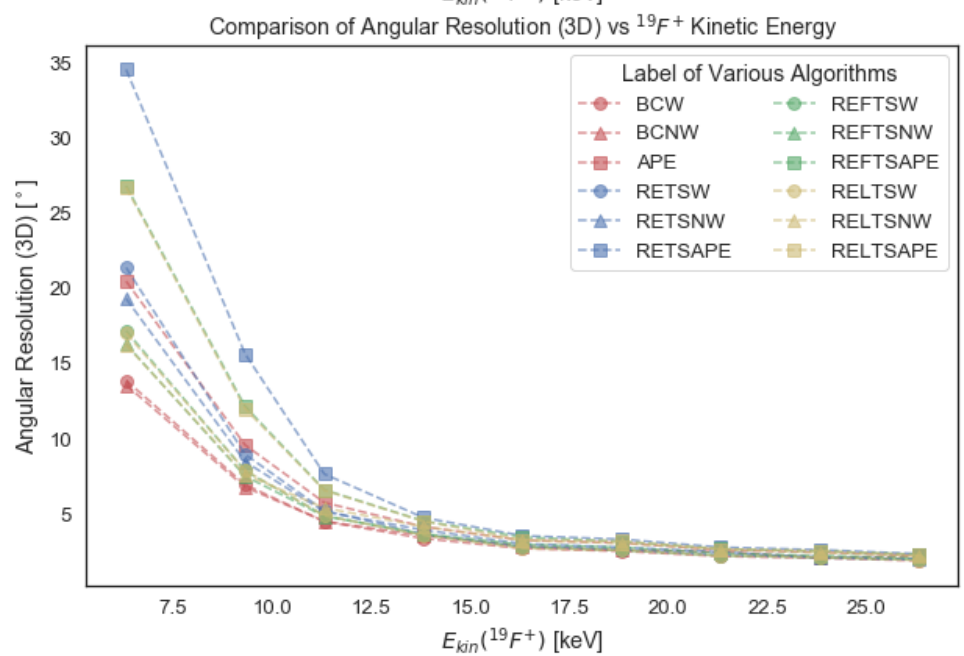

**Weight: number of pixels for each time slice**

# Comparison of Various Direction Reconstructed Algorithms

✳ **Upper:** Mean Angle Reconstruction

✳ **Lower:** Angular Resolution




**Conclusion:** **We finally apply the barycenter algorithm with weight, based on: 1) its stability on direction reconstruction and 2) its better angular resolution result.**

# Estimation of Uncertainty (Error Bar) for Angular Resolution

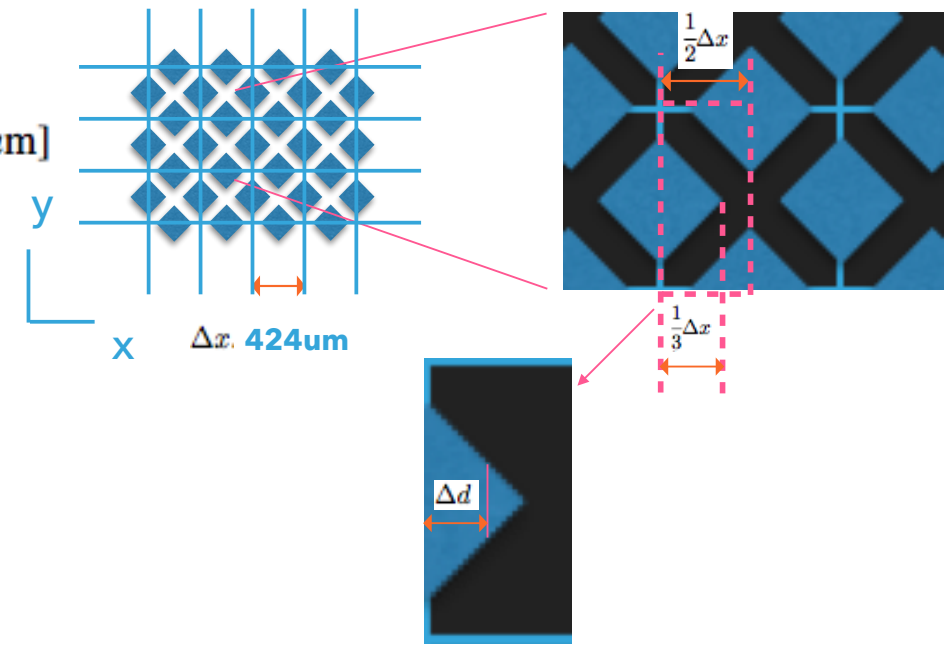
$$(\Delta\theta_{total})^2 = (\Delta\theta(x,y,z))^2 + (\Delta\theta_{statistics})^2$$

$$\Delta\theta_{statistics} = \frac{\sigma(\theta)}{\sqrt{N}}$$

$$\Delta\theta(x,y,z)\Big|_{\theta=<\theta>} = \frac{1}{z}\frac{1}{1+\tan^2<\theta>}\sqrt{\Delta_{XY}^2 + \tan^2<\theta> \cdot [V_{drift}^2\Delta^2(t) + t^2\Delta^2(V_{drift})]}$$

where,

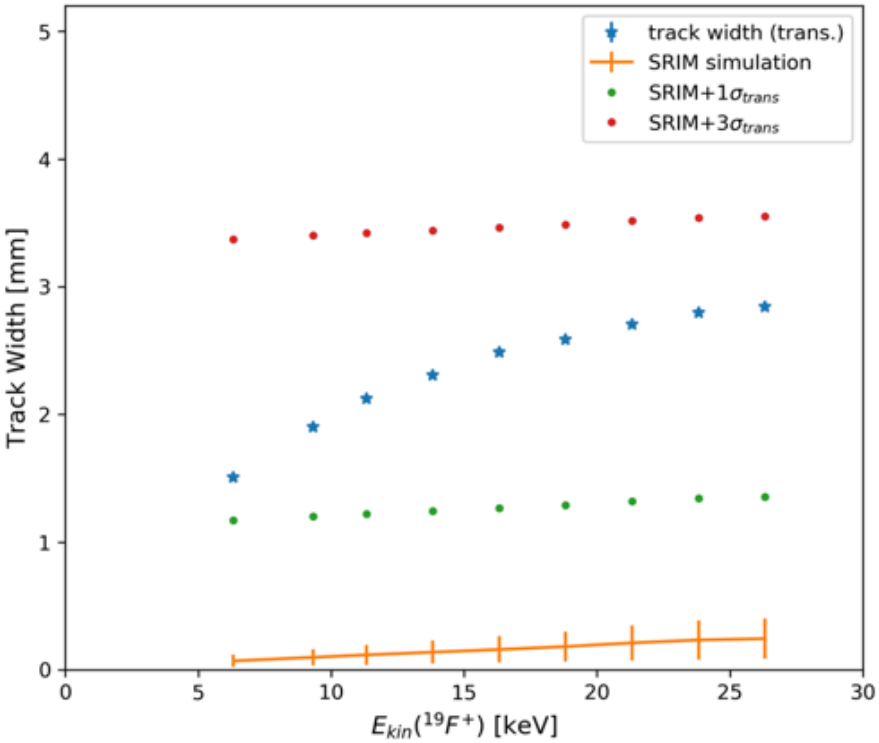
$$\Delta_{XY} = \Delta(x) = \Delta(y) = \Delta(pixel) = 57.7[\mu\text{m}]$$
$$\Delta(t) = 20[\text{ns}]$$
$$\Delta(V_{drift}) = 2.5\% V_{drift}$$



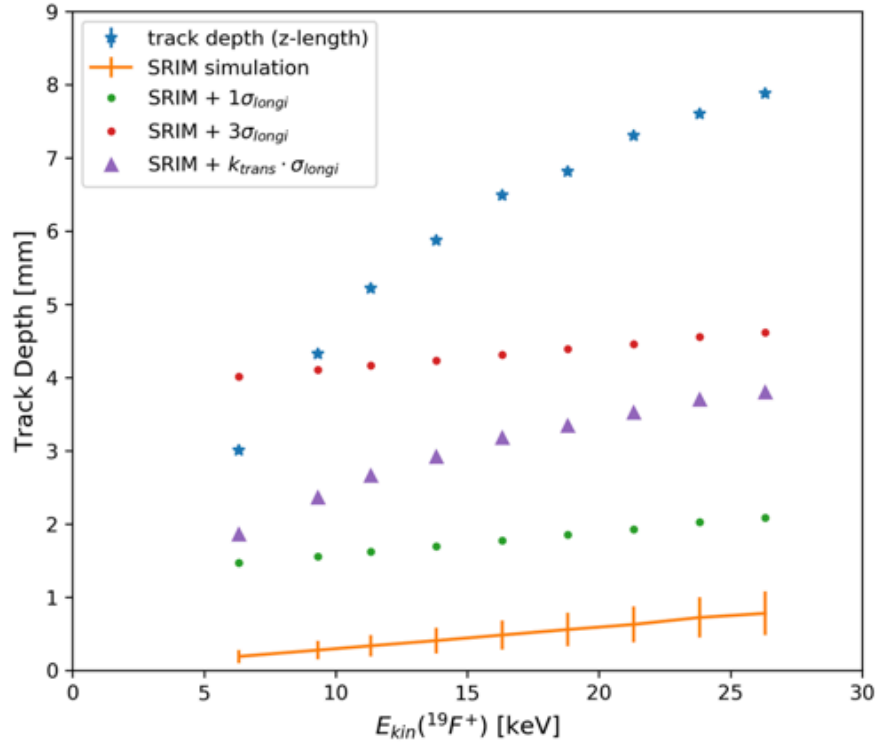
# MC Simulation (SRIM + MAGBOLTZ)

# Comparison with SRIM + MAGBOLTZ

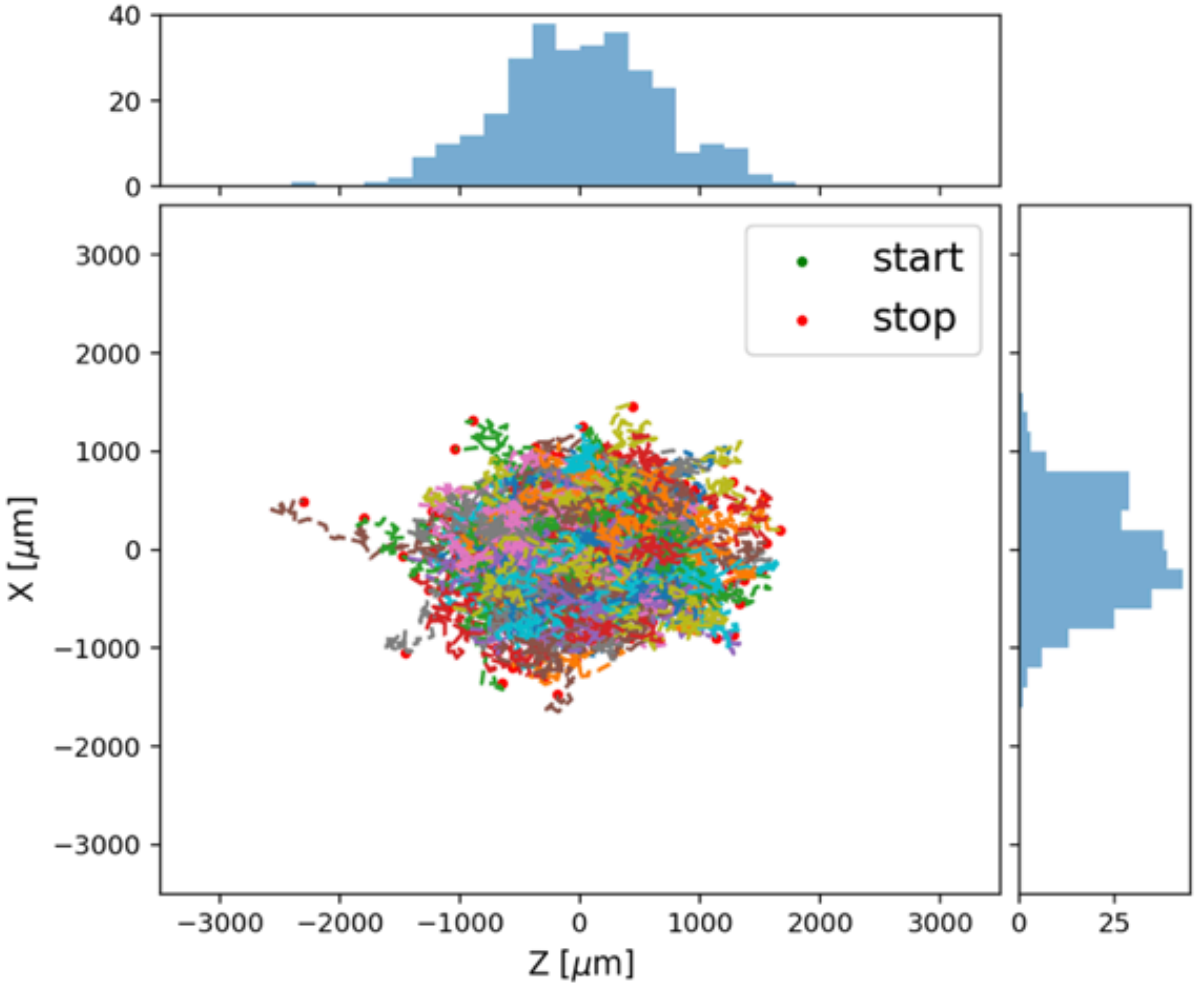
Width v.s. Ion Energy

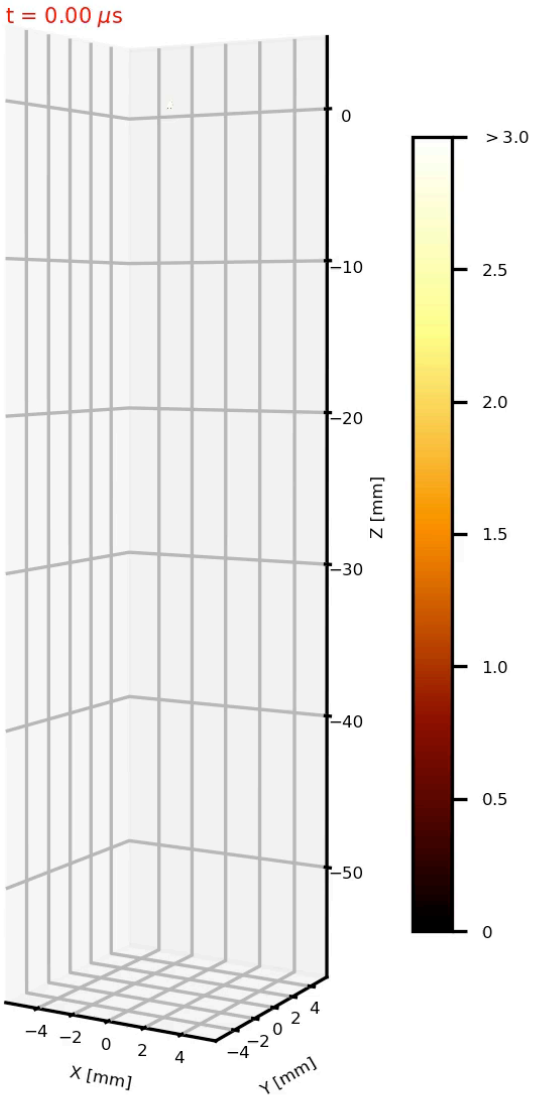



Depth v.s. Ion Energy



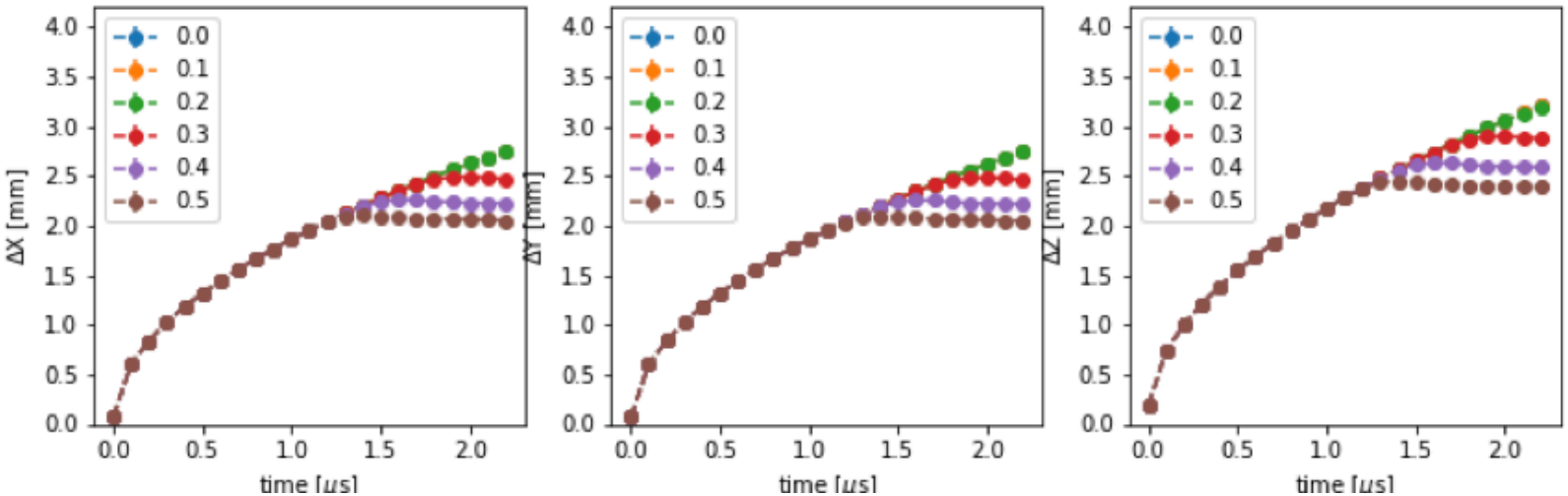
# 5 cm Drift Example



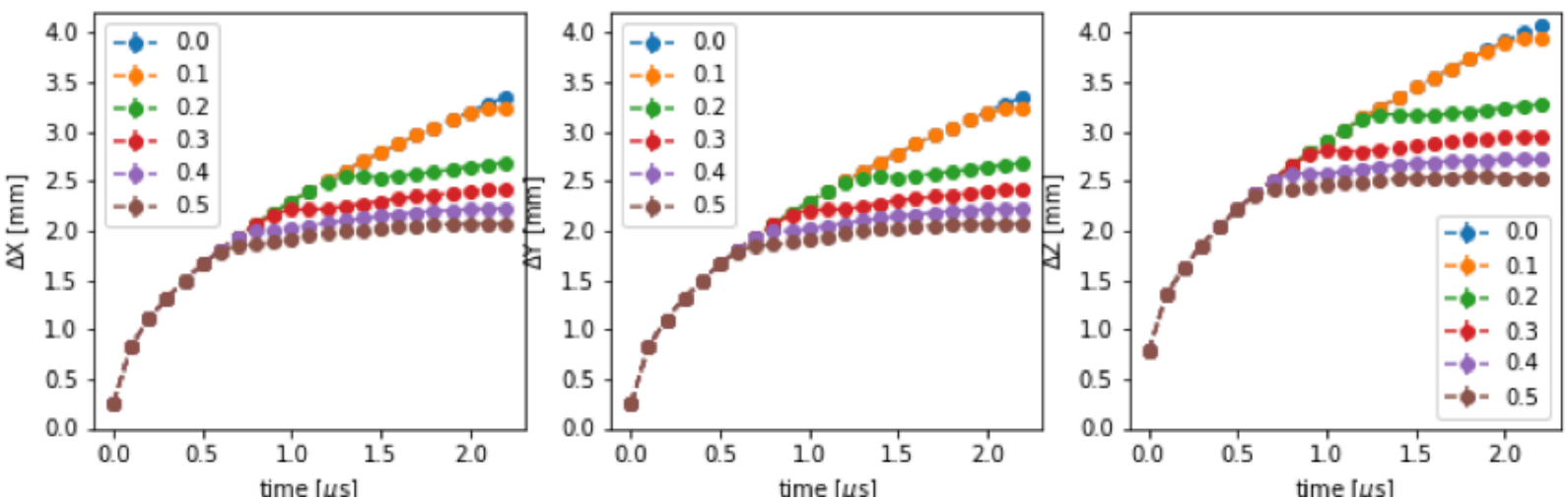



# Simulation Result — Detection Efficiency Effect / Gain

6.32keV




26.32keV



# Cathode Measurement

# MIMAC-Cathode Signal Drift velocity measurements

C. Couturier, Q. Riffard, N. Sauzet, O. Guillaudin, F. Naraghi, and D. Santos.
Journal of Instrumentation, 12(11):P11020, 2017b.

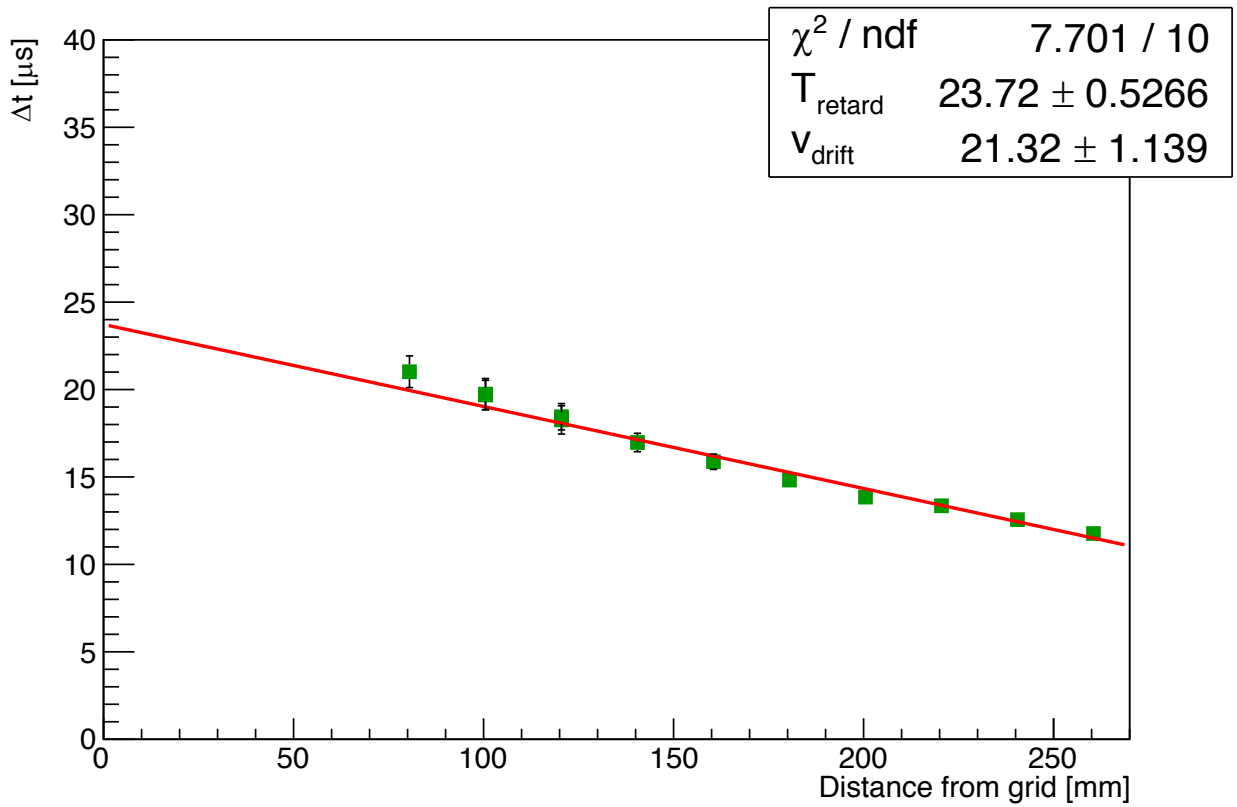
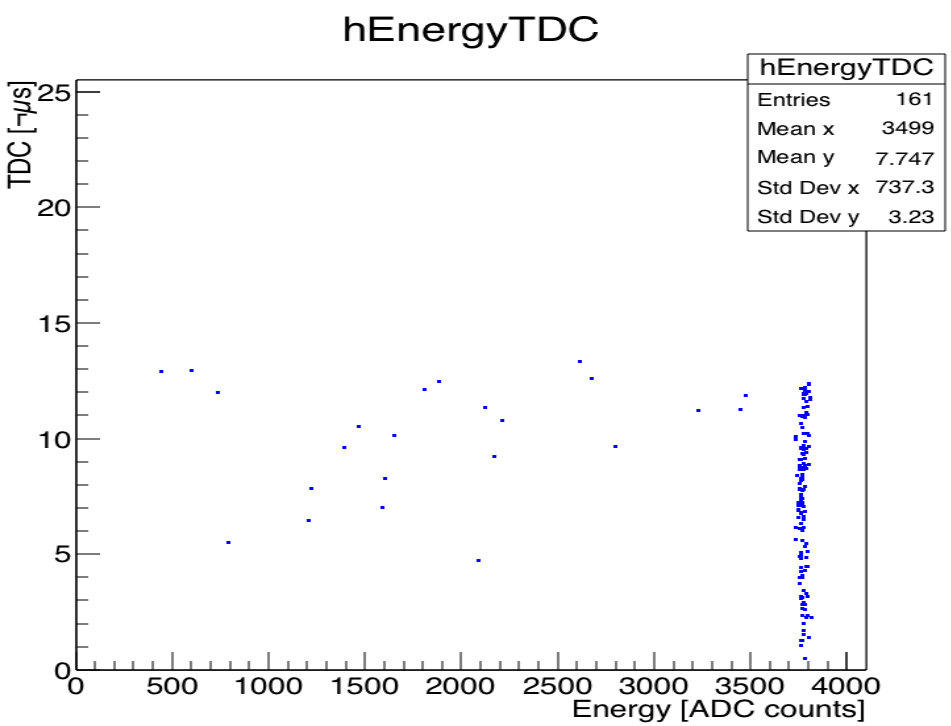
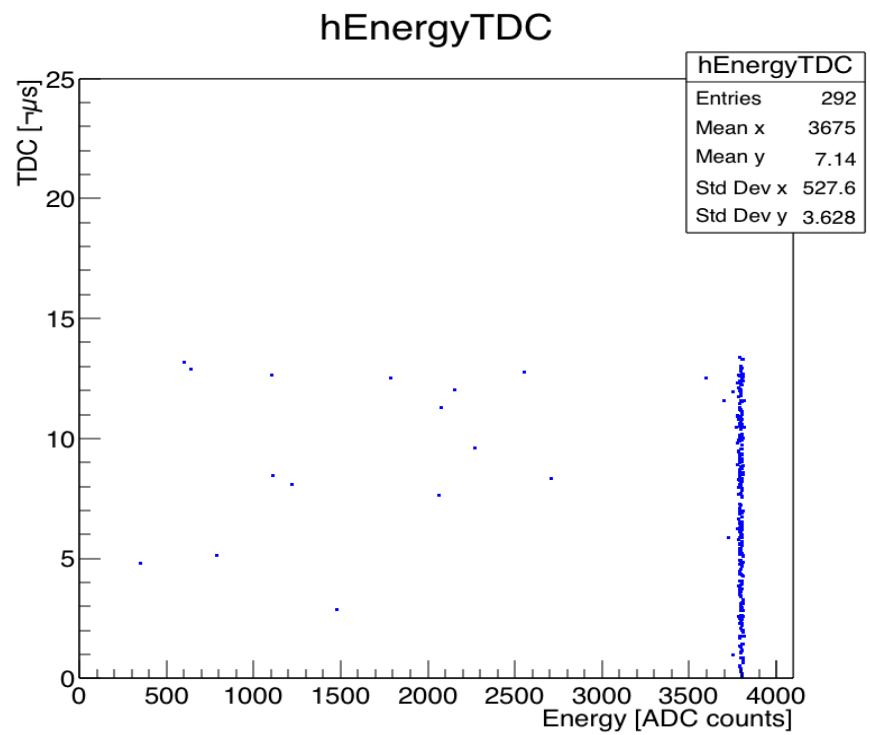



**Figure 4.** Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the $\alpha$ source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points is superimposed in red and provides the values of the drift velocity and the additional delay.

# Ionization Energy distribution of the events recorded with the Cathode Signal



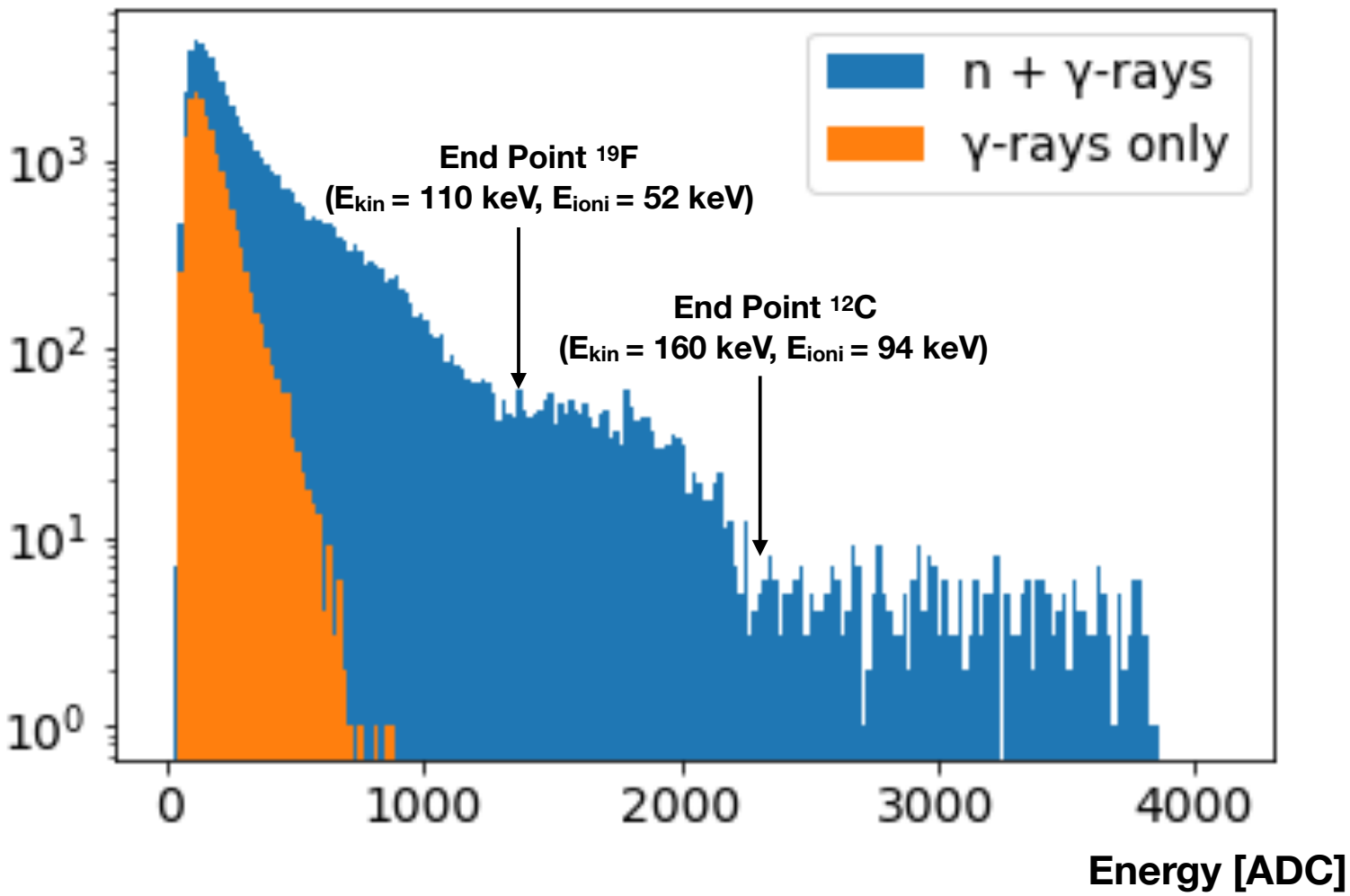




**Energy range: 1-60 keV**

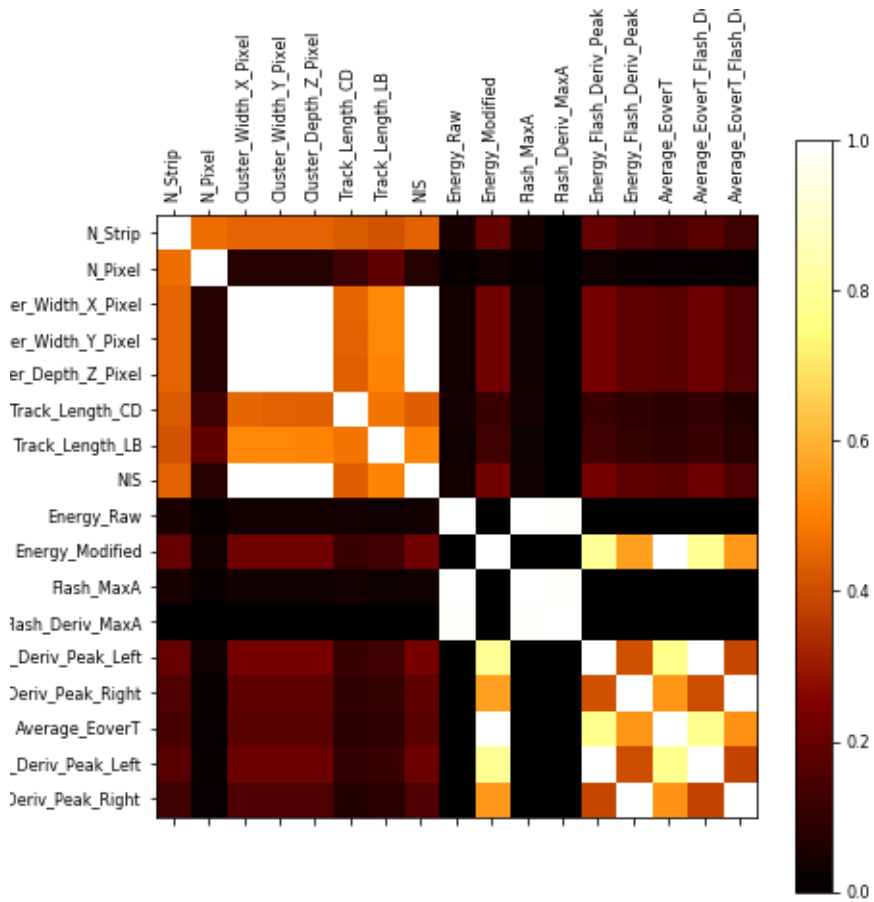
# Neutron Data Analysis (Preliminary)

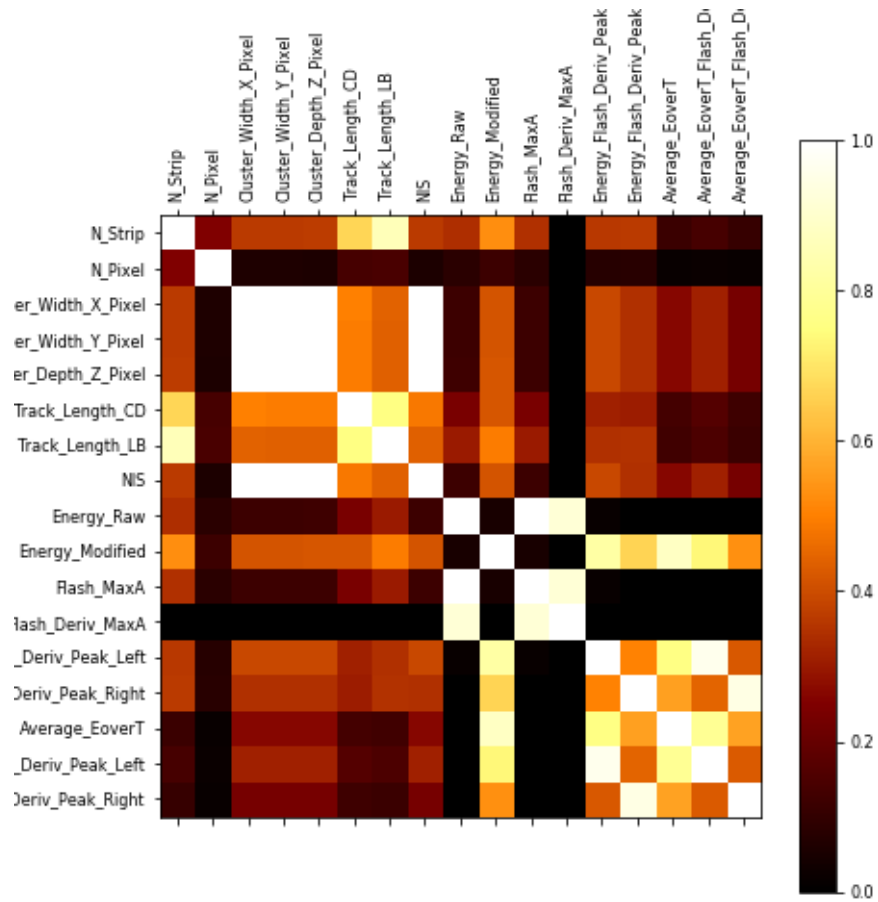
# Energy Spectrum

**565 keV Neutron**

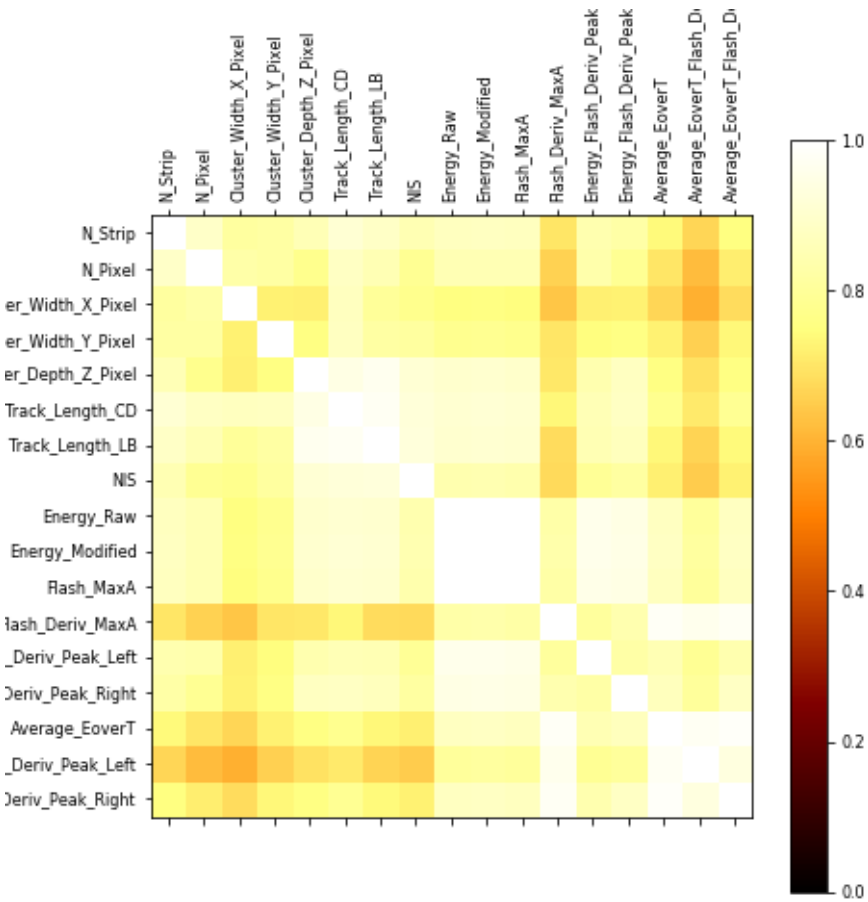


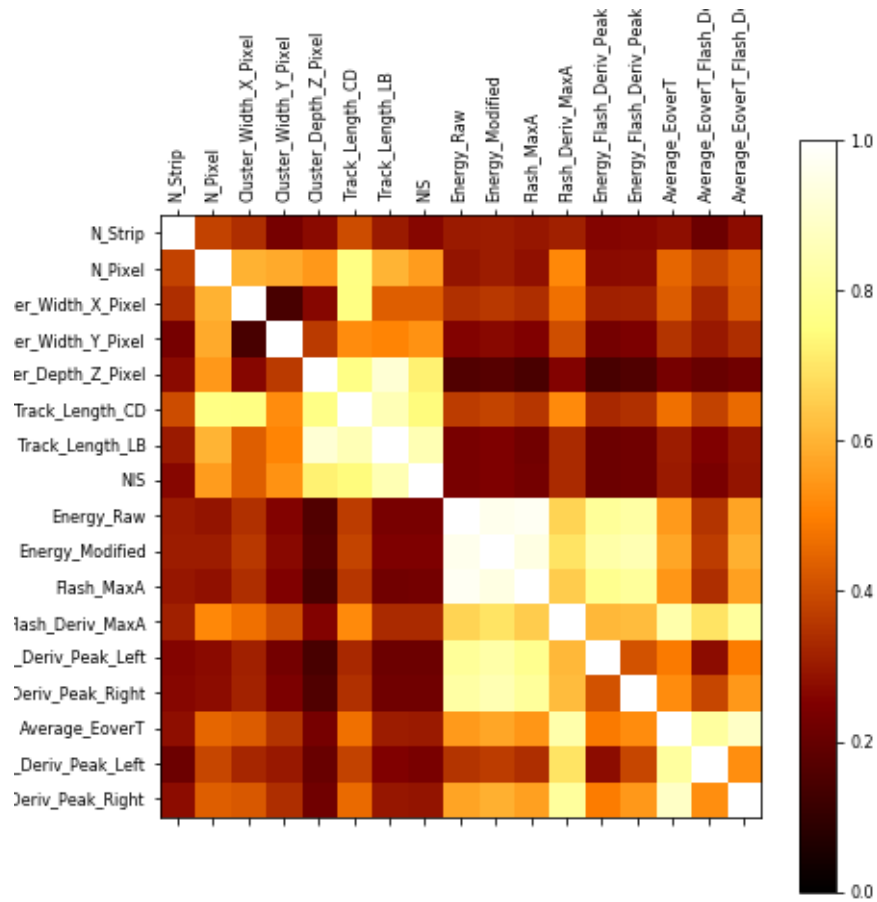
# Correlation Matrix: Before Event Filters



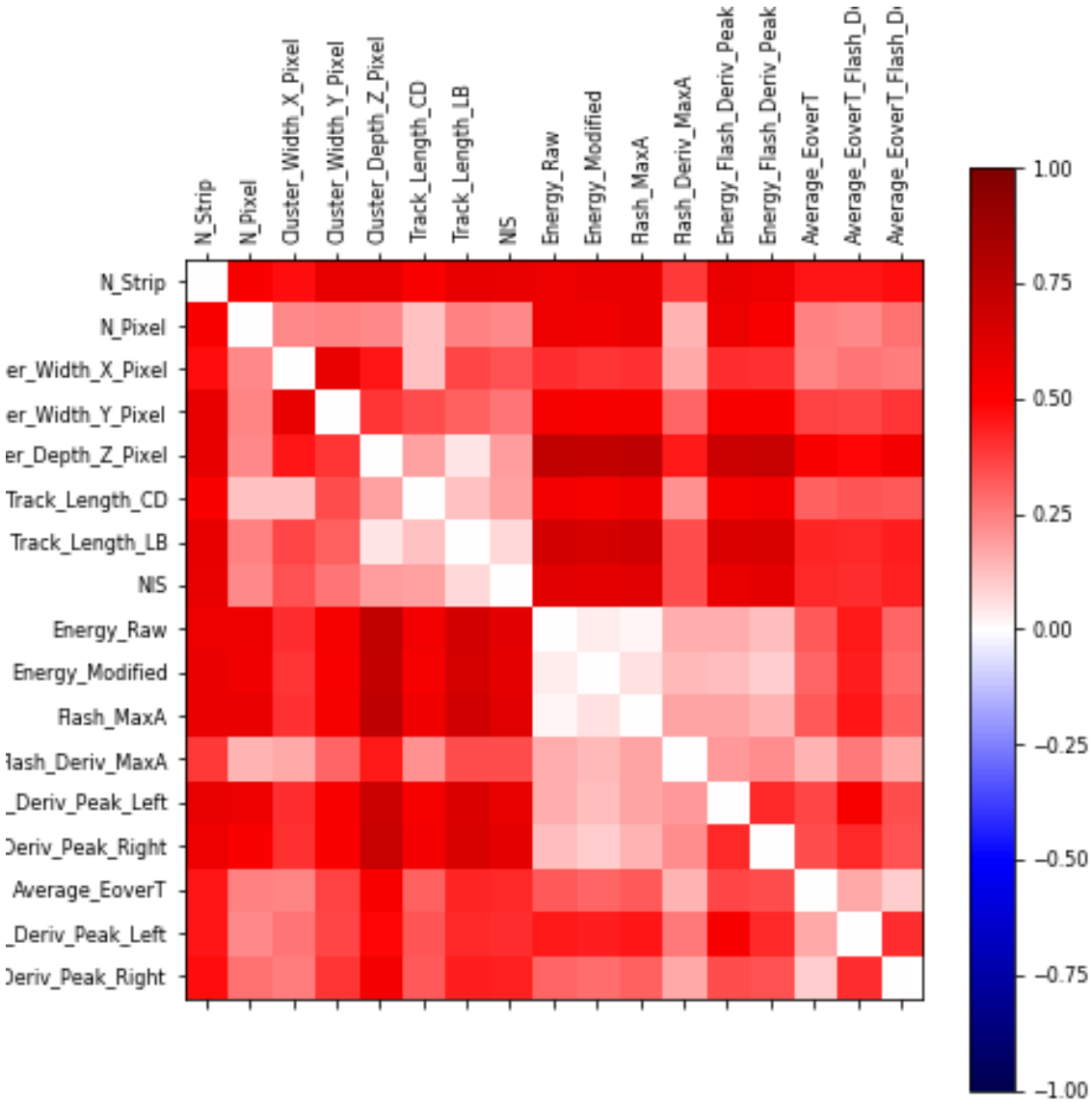



# Correlation Matrix: After Event Filters

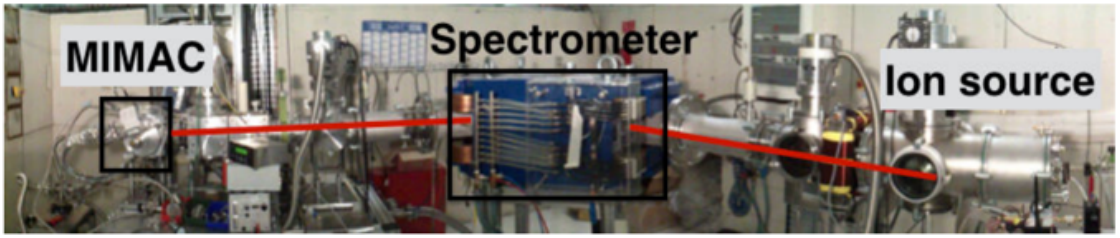


# Difference of Correlation Matrix



# Experimental Set-up




- **Target:** Fluorine (mass 19)
- **Beam Line (Source):** LHI
- **MIMAC detector:** Micromegas 10.8 $\times$ 10.8 $cm^2$
- **Gas:** MIMAC gas (70%$CF_4$ + 28%$CHF_3$ + 2%$iC_4H_{10}$)
- **Drift Distance:** 5 cm
- **Sampling Time:** 20 ns
- **HV: Cathode:** 1320 V **Grid/Mesh:** 570 V

  **=> Drift Field:** 150 V/cm => **Drift Velocity:** 22.87 um/ns
- **Avalanching Gap:** 512 um
- **Calibration Source:** $^{55}Fe$ **X-ray**
- **Kinetic Energy of Fluorine (keV):**

  6.32, 9.32, 11.32, 13.82, 16.32, 18.82, 21.32, 23.82, 26.32