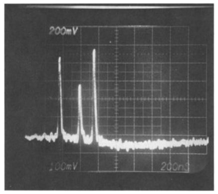

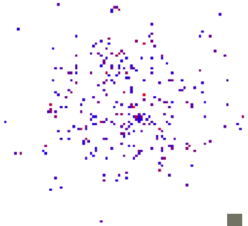

Experimental Techniques of Charge-based Cluster Counting

Jochen Kaminski
University of Bonn

RD51 Workshop on Gaseous Detector Contributions to PID
zoom
17.2.2021

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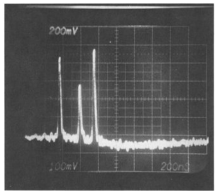
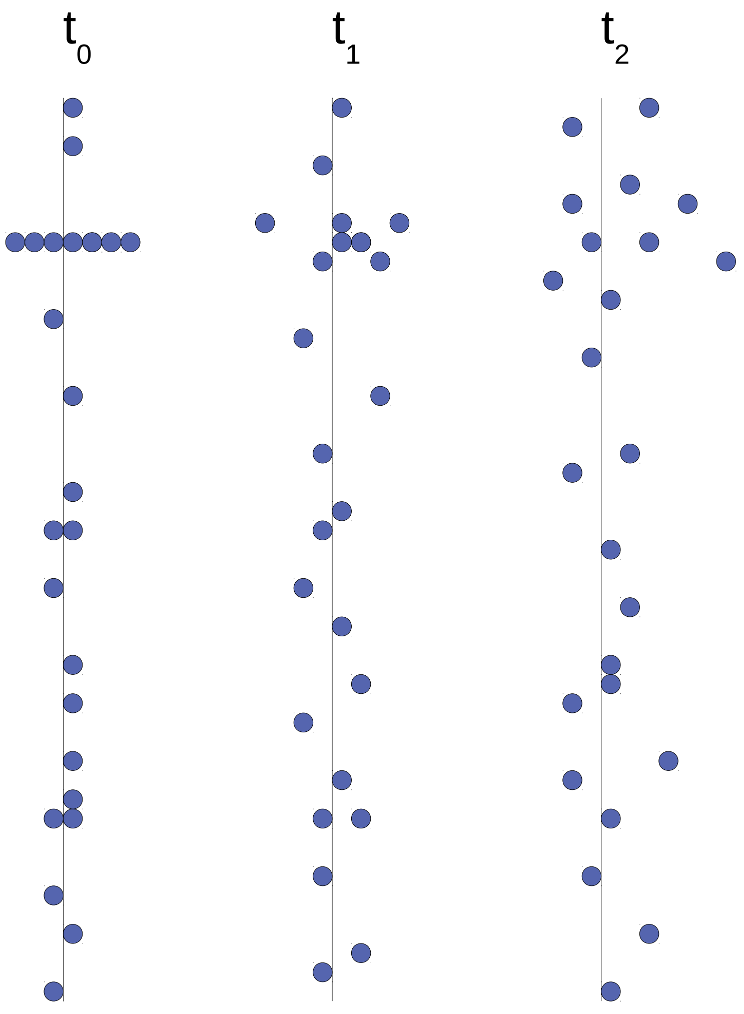


The Experimental Challenge



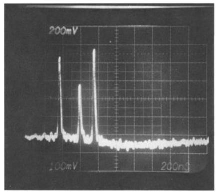
Charged particles create ion/electron pairs along their track. The charge is clustered by primary interactions, which create mostly one i/e pair, but can also create several or many i/e pairs.

Counting primary interactions (N_P) has advantages over integrating the charge.

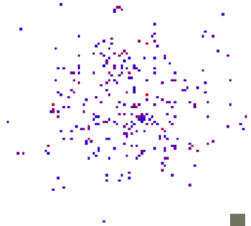
The challenge is to beat the diffusion!
Requirements are therefore:

- Low diffusion compared to cluster distance
- High resolution readout
- No electronegative gases (losing primary charge)

Experimental approaches:
1.) Time-based paradigm – the classical approach
2.) Space-based paradigm – the MPGD approach



Comparison of Gases

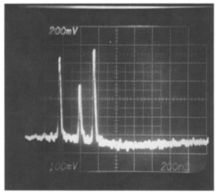


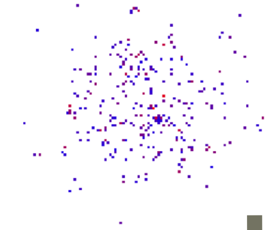
low ωτ gas with high/low ionization density (Ar:CO_2 and He:CO_2)

high ωτ gas with high/low ionization density (Ar:CF_4:iC_4H_{10} and Ar:CH_4:iC_4H_{10})

gas	E $\left[\frac{V}{cm}\right]$	D_T $\left[\frac{\mu m}{\sqrt{cm}}\right]$ $= \sigma_T(1\ cm)$	D_L $\left[\frac{\mu m}{\sqrt{cm}}\right]$ $= \sigma_L(1\ cm)$	v_{drift} $\left[\frac{cm}{\mu s}\right]$	N_P $\left[\frac{1}{cm}\right]$	N_T $\left[\frac{1}{cm}\right]$	$\frac{1}{N_P} = T_P = \frac{1}{N_P \cdot v_{drift}} = \Delta\sigma_T(1\ cm) = \Delta\sigma_L(1\ cm)$
Ar:CO_2 80:20 $B = 0$ T	500	160 ± 4	189 ± 4	1.918 ± 0.001	27	97.6	370 μm $= 19.31$ ns $= 2.31$ $= 1.96$
He:CO_2 80:20 $B = 0$ T	500	144 ± 3	142 ± 4	1.225 ± 0.001	9.8	26.4	1020 μm $= 83.29$ ns $= 7.1$ $= 7.2$
Ar:CF_4:iC_4H_{10} 95:3:2 $B = 0$ T	286	324 ± 5	200 ± 3	7.891 ± 0.001	27.5	100	364 μm $= 4.6$ ns $= 1.12$ $= 1.81$
Ar:CH_4:iC_4H_{10} 95:3:2 $B = 4$ T	286	33.5 ± 0.7	201.3 ± 5.5	7.891 ± 0.001	27.5	100	364 μm $= 4.6$ ns $= 10.9$ $= 1.81$

Data: Magboltz and PDG



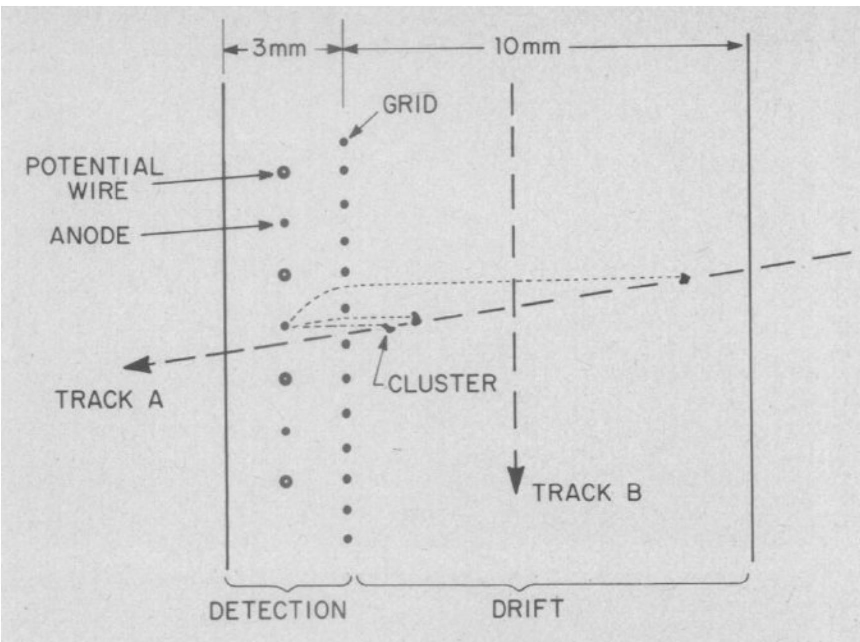


The Time-based Paradigm (I)
First Measurements

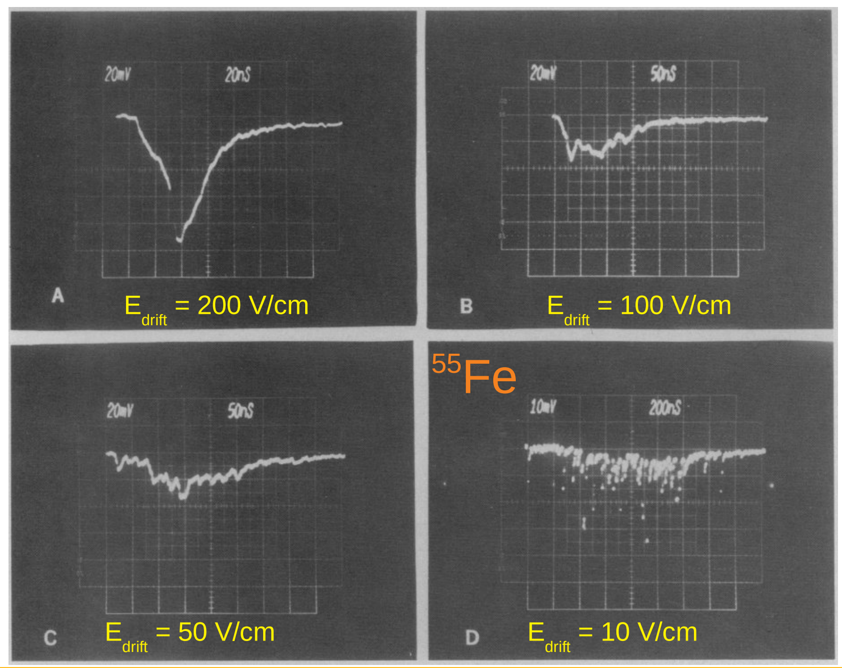
First suggested in the 70s; first measurements of cluster sizes by A. H. Walenta in 1979: IEEE TNS, NS-26, No. 1, 1979, p. 73-80

Initial problem: ‘The response of the counter to a single cluster is too slow compared to the mean drift distance.’ → Cluster are overlapping too much and can not be separated.

Solution: Time Expansion Chamber: Reduce drift velocity/field in drift region to increase time between clusters
high field in detection region → fast signals

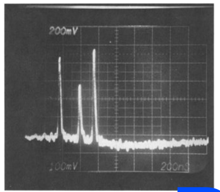


Electrode arrangement and principle of the TEC. Track A for ionization loss measurement, track B for position measurement.

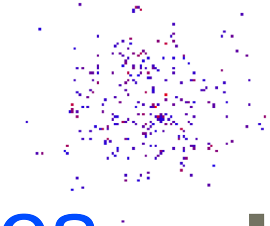


Using
- A current amplifier with 4 ns rise time
- Updating discriminator
- 100 MHz scaler

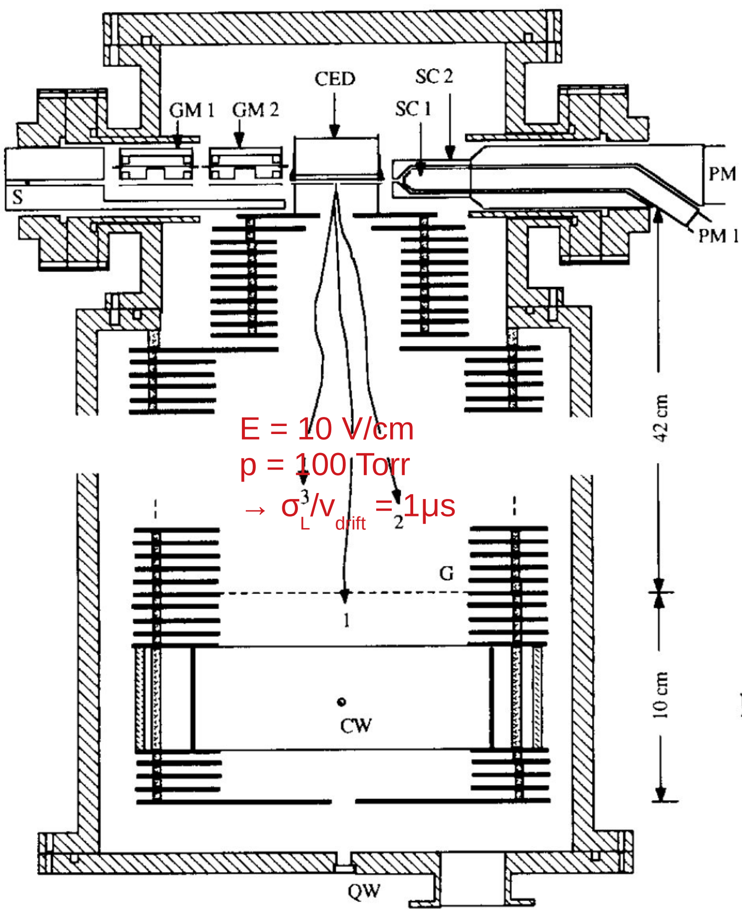
=> count clusters of tracks



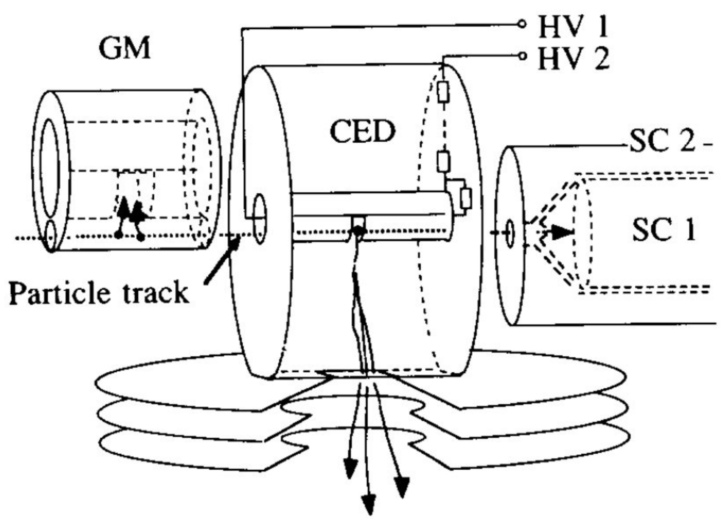
The Time-based Paradigm (II)
Precision Measurement of Cluster Sizes

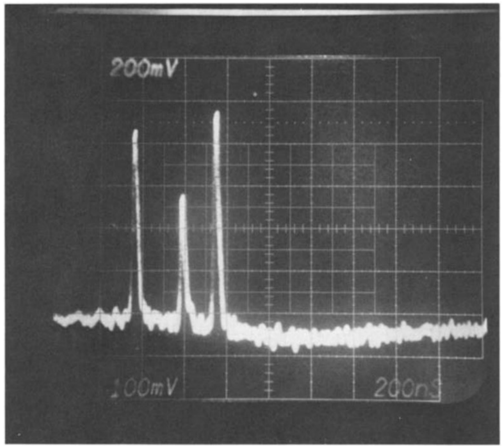


H. Fischle, J. Heintze, B. Schmidt, “Experimental determination of ionization cluster size distributions in counting gases”, NIMA 301 (1991) 202-214

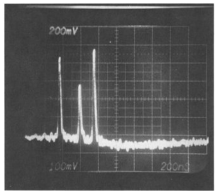


The detector operated at 100 Torr.
The opening slit is 1 mm wide:
→ 10-20% probability of 1 cluster
→ very low probability of 2 or more clusters
→ Electrons extracted to drift region

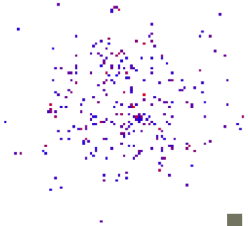




Electronics:
- High-gain common-base amplifier with a FET source follower
- Gaussian filter
- 100 MHz FADC
  (2nd input with 5ns delay)
- Complicated trigger
  with GMs, SCs



The Time-based Paradigm (III) Designs for Particle Physics Exp.

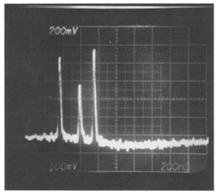


After 2000 cluster counting was suggested for usage in several experiments and some examples are

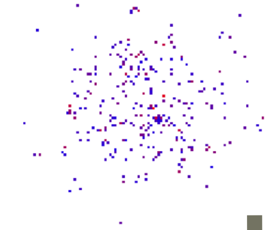
- Detector for ILC (4th Concept)
- Detector for SuperB
- Detector for FCC-ee (IDEA)

Prototypes with single drift chamber cells have been tested in test beam setups. High efficiencies could be demonstrated.

Some aspects typical for all setups are shown on the following slides.



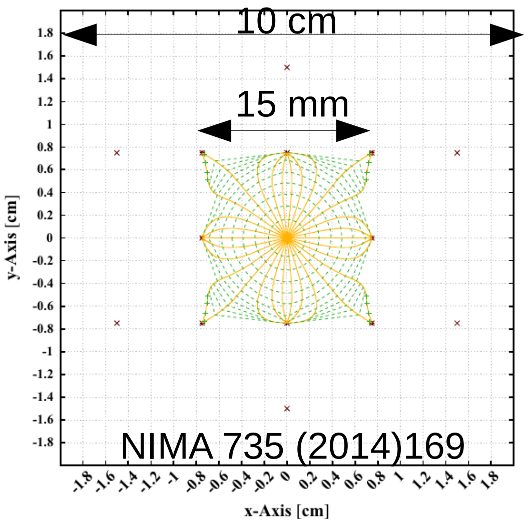
The Time-based Paradigm (IV) Detector Setups



Gas mixture: often helium based gas mixtures is chose because of multiple scattering considerations of the respective experiments (mostly He:iC_4H_{10} 90:10).

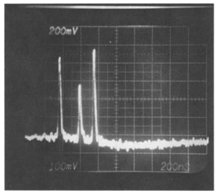
Mostly long single cell prototype detectors are used (2-3 m).
Diameters of drift cells are 10-20 mm.
Either in large drift chambers with sense and field wires, or in separate cylindrical form.

High gas gains do not improve cluster counting → medium gas gains are better

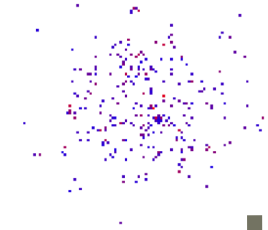


Particles should transverse the detector perpendicular to the sense wire.

Important are the electronic termination of the signal at the HV end (≠readout end).



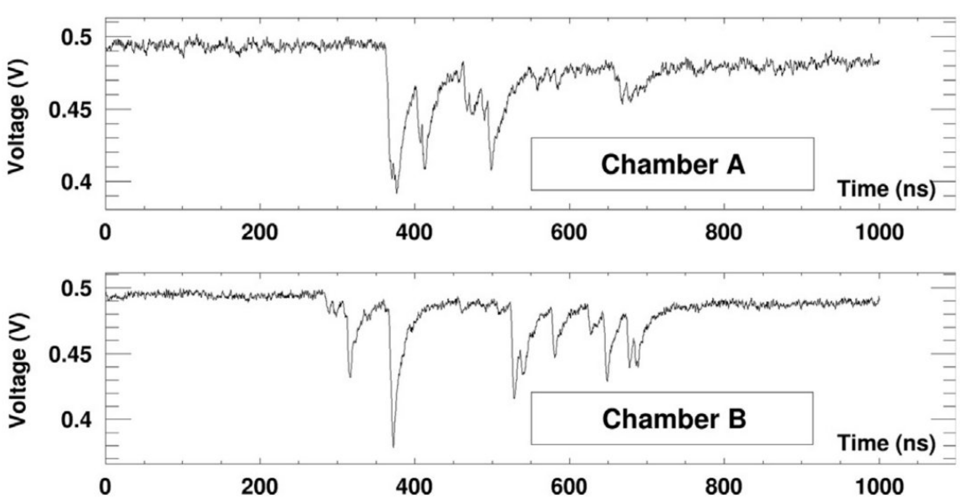
The Time-based Paradigm (V) Readout Electronics



All electronics made for tests were home made for 1 or 2 channels and not scalable.

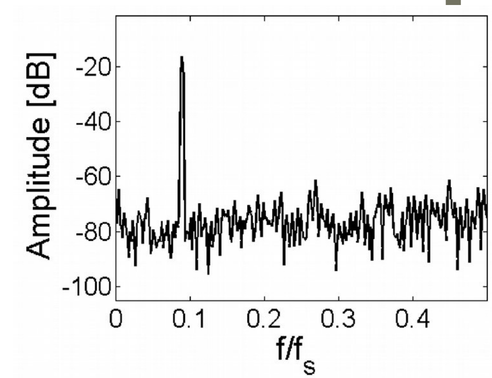
Signals of single clusters have a raise time of 2-5 ns.

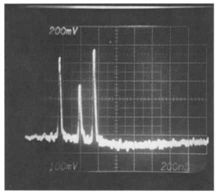
Preamps are usually standard opamp stages (e.g. current/voltage converters) with high bandwidth: 125 MHz – to 3 GHz, but high bandwidth is not necessary. Several hundred MHz are enough.
+ Some limited shaping
+ Digitization with a high band width oscilloscope, bandwidth <= 1 GHz is enough.



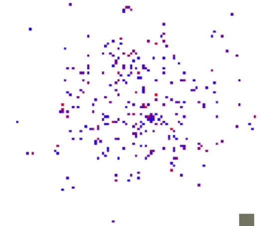
NIMA 735 (2014)169

A dedicated ASIC for cluster counting was designed for ILC (IEEE Proc. IWASI 2007):
Technology: 130 nm CMOS
ADC resolution: 6 bit
Clock frequency: 1 GHz
Sample rate: 1 Gsa/s
→ not sure if it was ever produced, maybe a 1 channel test ASIC

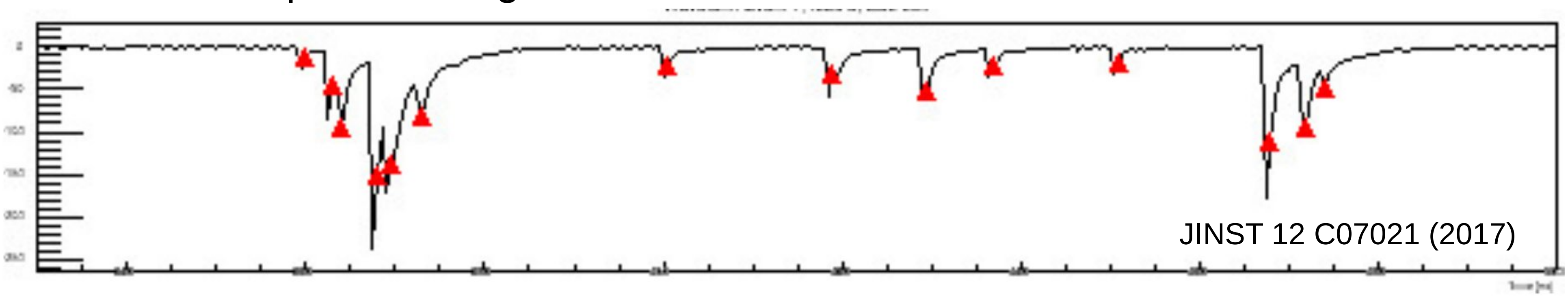




The Time-based Paradigm (VI) Reconstruction / Analysis Methods



As signals of electrons of a single cluster are expected to be merged, the analysis is reduced to a peak finding:



Often the signal V is smoothed $\overline{V}$ (hence high bandwidth electronics is not needed). Then first derivative is taken

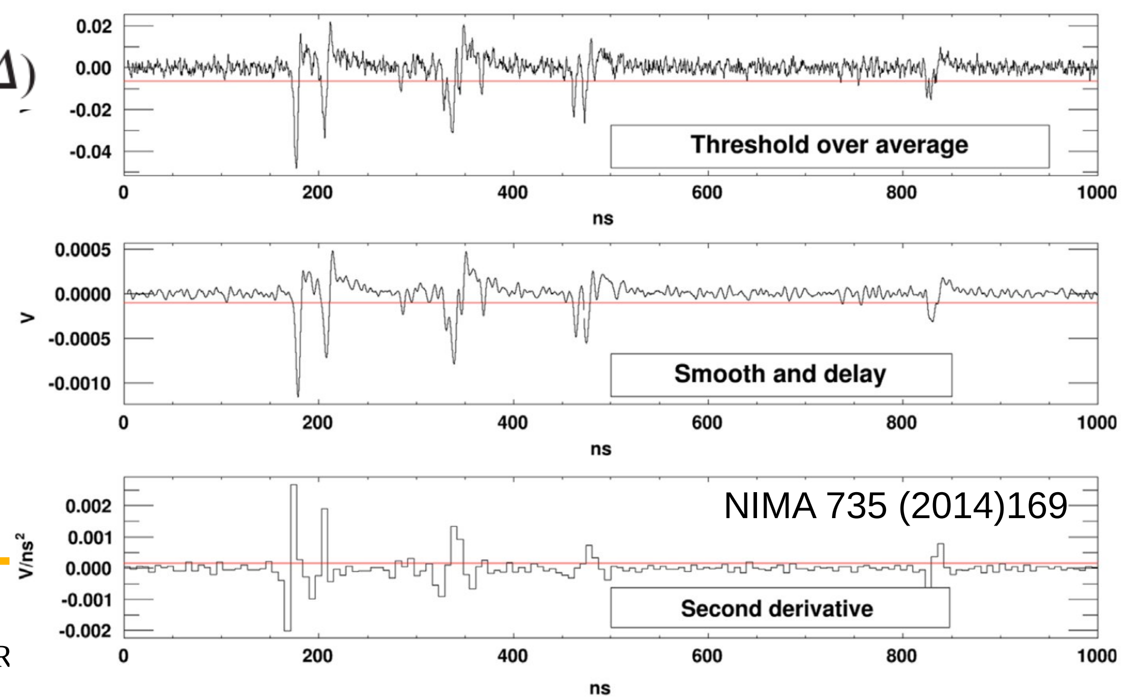
$$(V(t)-\tilde{V}_n(t-1)<\Delta)\,\&\,(V(t)-\tilde{V}_n(t-1)<\Delta)$$

or a more general term of the first derivative: $\frac{\tilde{V}_p(t)-\tilde{V}_q(t-d)}{d}<\Delta$

or a second derivative

$$\overline{V}''(\bar{t})=\frac{1}{\delta^2}([\overline{V}(\bar{t}+2)-\overline{V}(\bar{t}+1)]-[\overline{V}(\bar{t}+1)-\overline{V}(\bar{t})])$$

Algorithms can be implemented on FPGA (JINST 12 C07021 (2017).



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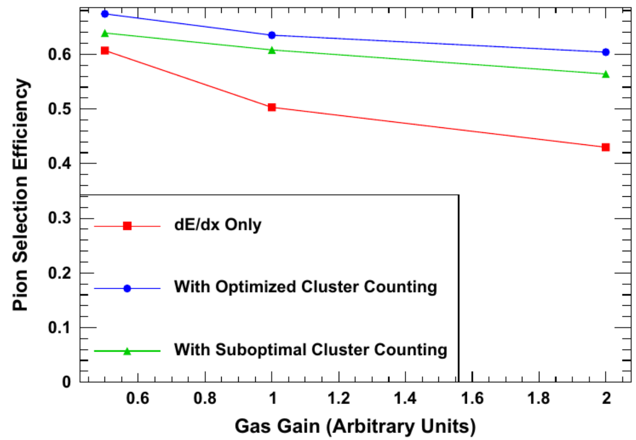
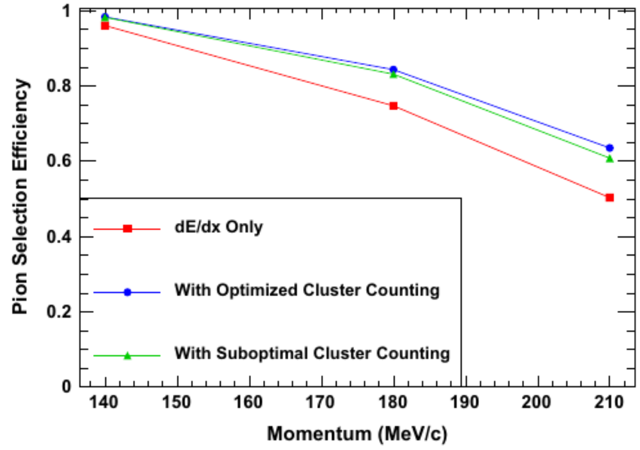
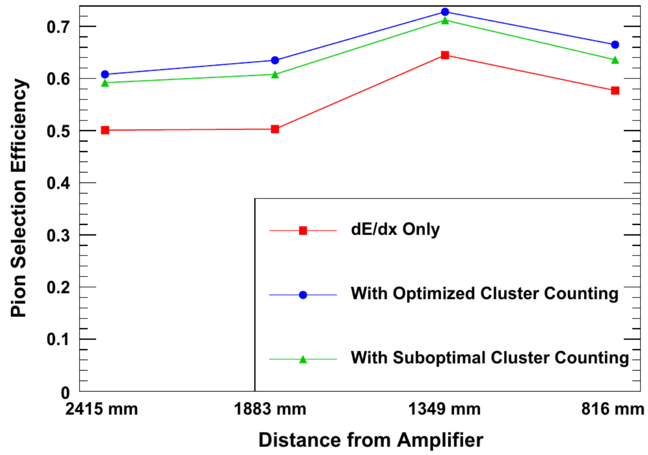
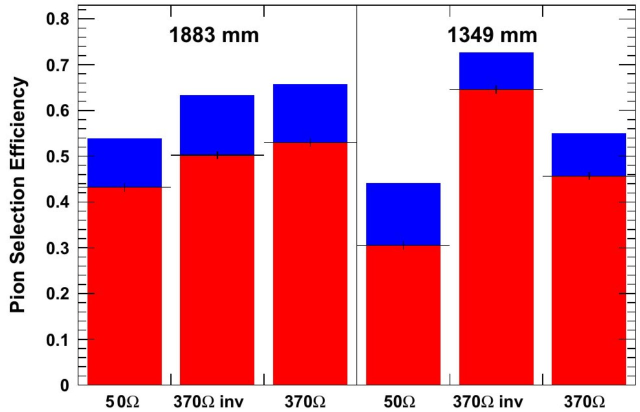
The Time-based Paradigm (VII) Performance

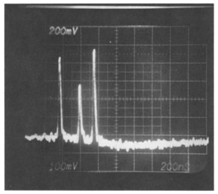
In the paper NIMA 735 (2014)169 the efficiency of positron, muon and kaon separation is studied. Different likelihoods are built and the effects of various setups are compared.



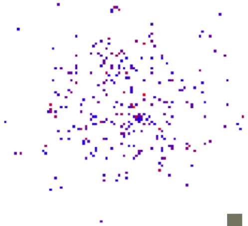








The Space-based Paradigm (I)
Optimization of Pad Size



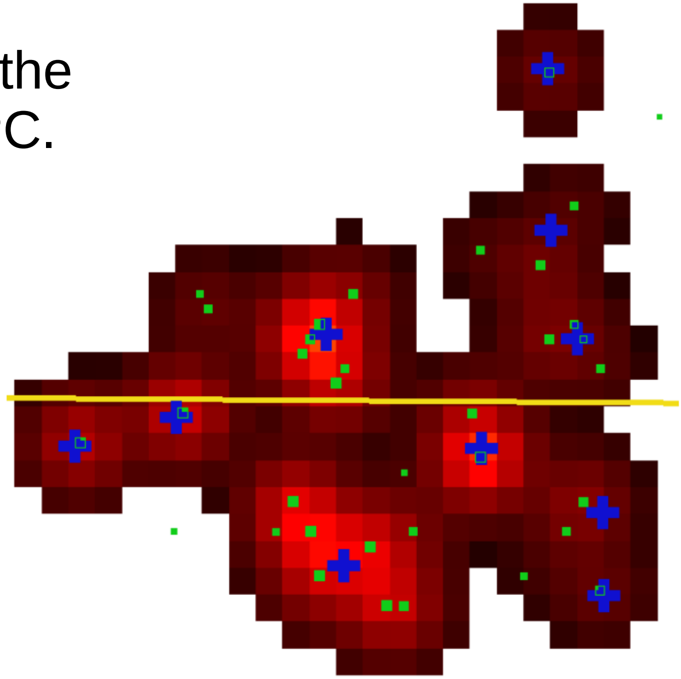
A simulation was performed by U. Einhaus (DESY) to optimize the pad size for PID with dE/dx and cluster counting for a potential ILD TPC.

The creation and diffusion of the electrons as well as the was the event reconstruction was done with MarlinTPC.

A signal broadening of a triple GEM stack was used.

As a figure of merit the separation power of pions and kaons was chosen:

$$S = \frac{|\mu_\pi - \mu_K|}{\sqrt{(\sigma_\pi^2 + \sigma_K^2)/2}}$$



Simulated charge distribution on 200 µm wide pads (arXiv: 1902.05519)

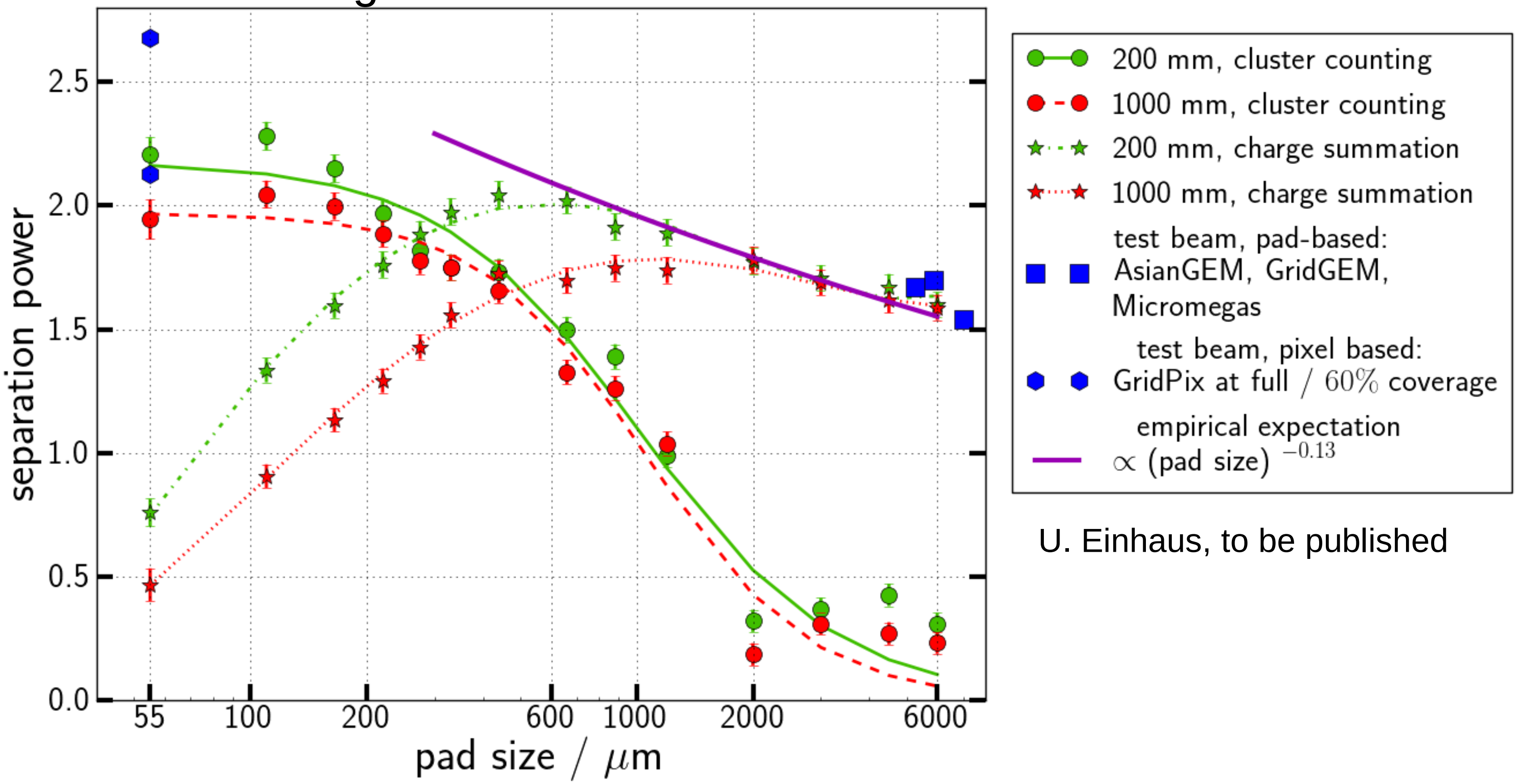
The Space-based Paradigm (I)
Optimization of Pad Size

Separation power of pions and kaon at ILD conditions:

B = 3.5 T, $E_{\pi/K}$ ~ 3 GeV

Gas mixture: $Ar:CF_4:iC_4H_{10}$ 95:3:2,

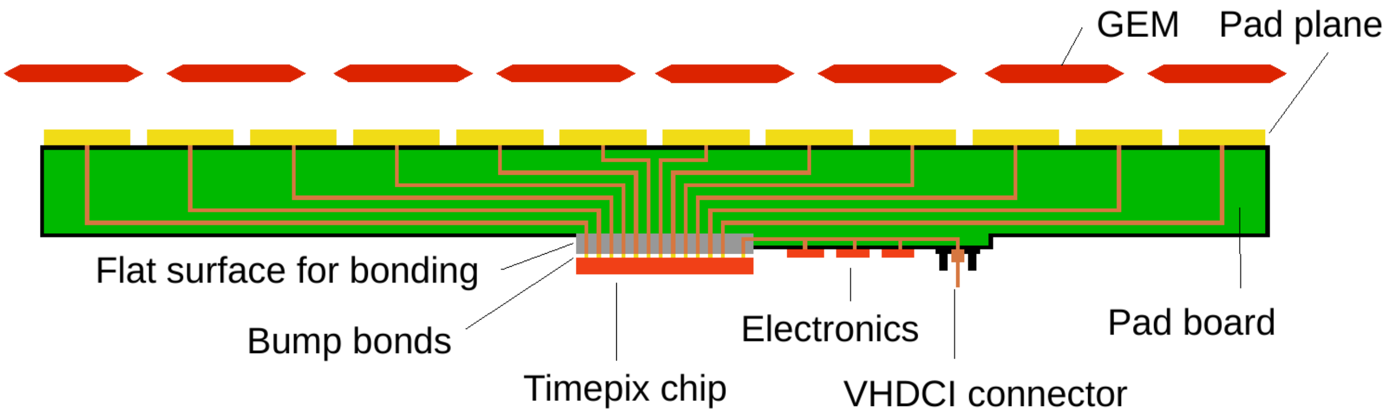
track length: 1.35 m

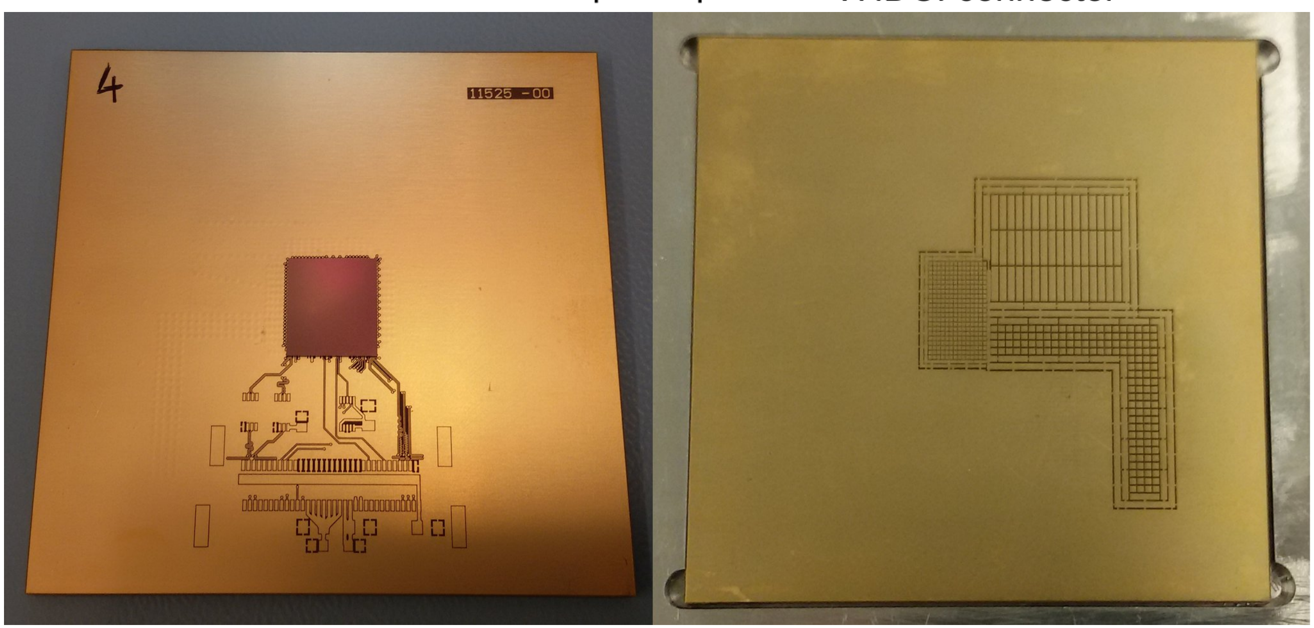


U. Einhaus, to be published

The Space-based Paradigm (II)
ROPPERI – Readout of Small Pads

Challenge for small pads: Reach high electronics density



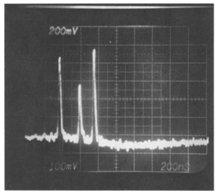


Idea: Connect pixel chip (Timepix) on backside of readout plane with gold stud bump bonds

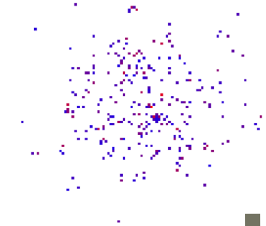
Problem: Chips heat up in operation and has a different expansion coefficient than PCB
→ bump bonds break

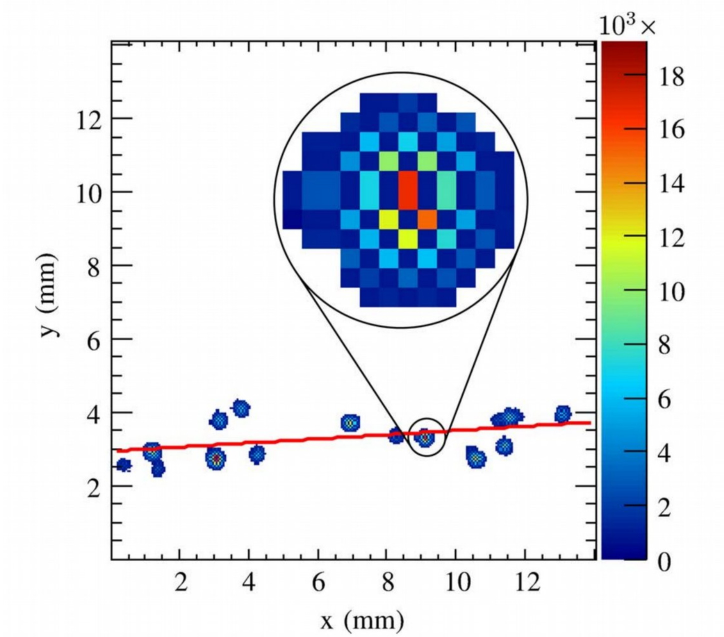
Results sofar: Noise because of large capacitances seem manageable, increase of noise because of larger pads could be verified

U. Einhaus, to be published



The Space-based Paradigm (III) GEMs with Timepix





Test setup of a TPC (26 cm) and cosmic muon trigger:

Gas mixture: $He:CO_2$ 70:30

Amplification: triple GEM, 1 mm spacings

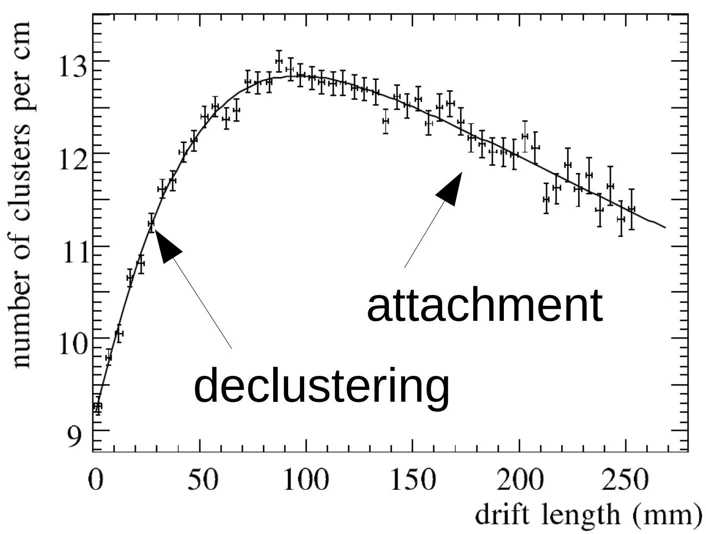
Gas gain: ~160,000

Readout: single Timepix

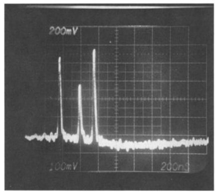
Expect: N_P=13 and N_T = 36

A maximum of 13 clusters was seen:

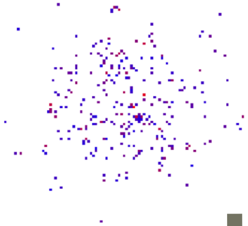
- Strong effect of declustering is observed
- doubts that this is cluster counting and not low efficiency



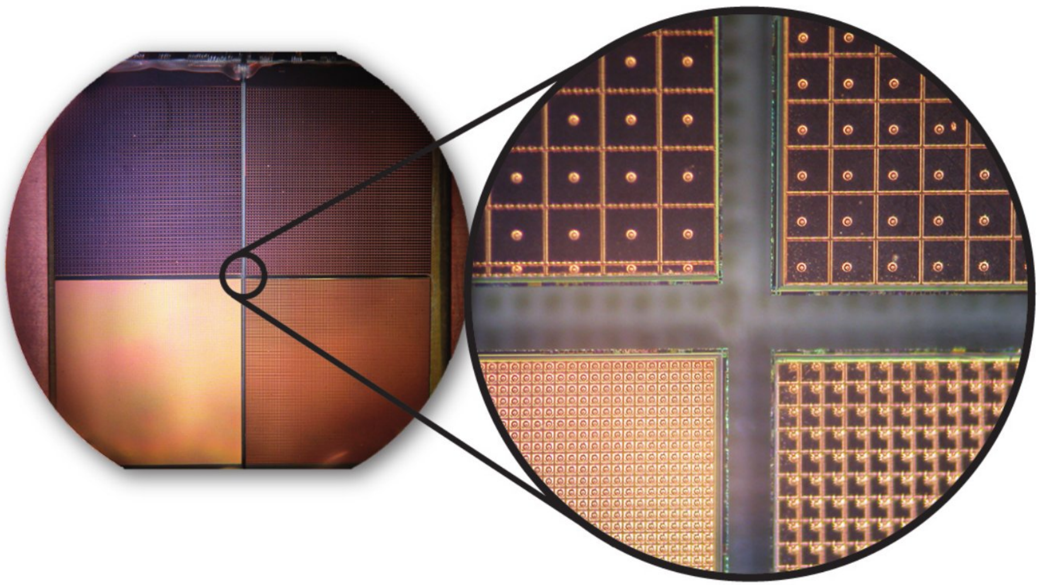
IEEE TNS, VOL 59, NO 6, 2012, 3221



The Space-based Paradigm (IV) Larger Pixel Sizes



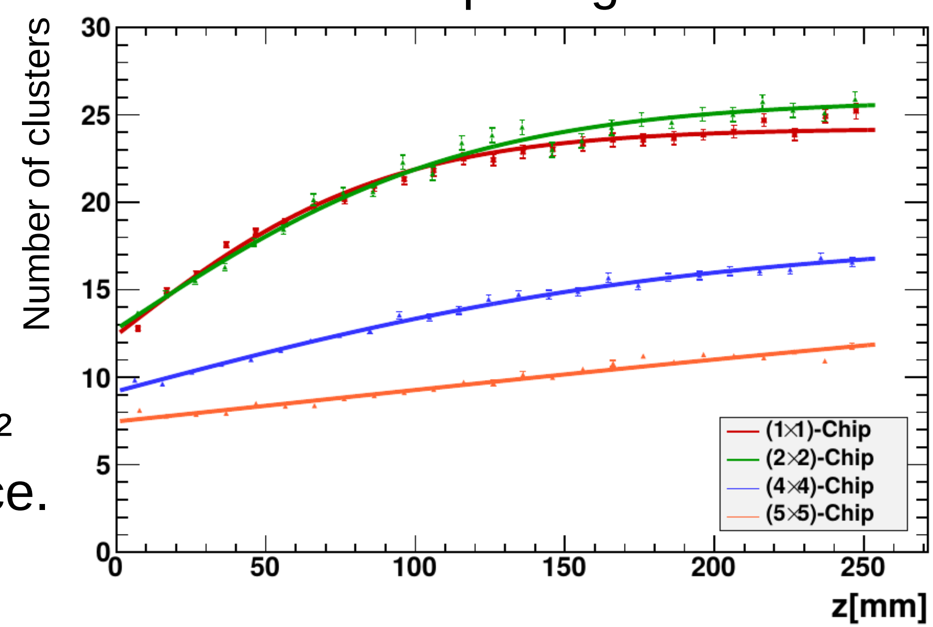
To collect more charge per pixel, we combined Timepix pixels 1x1, 2x2, 4x4, 5x5



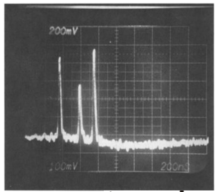
Chips modified by adding larger copper pads on top of an insulating layer.

Gas mixture: He:CO_2 70:30

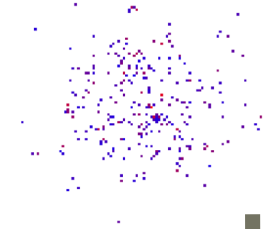
Amplification: triple GEM with 1 mm spacings

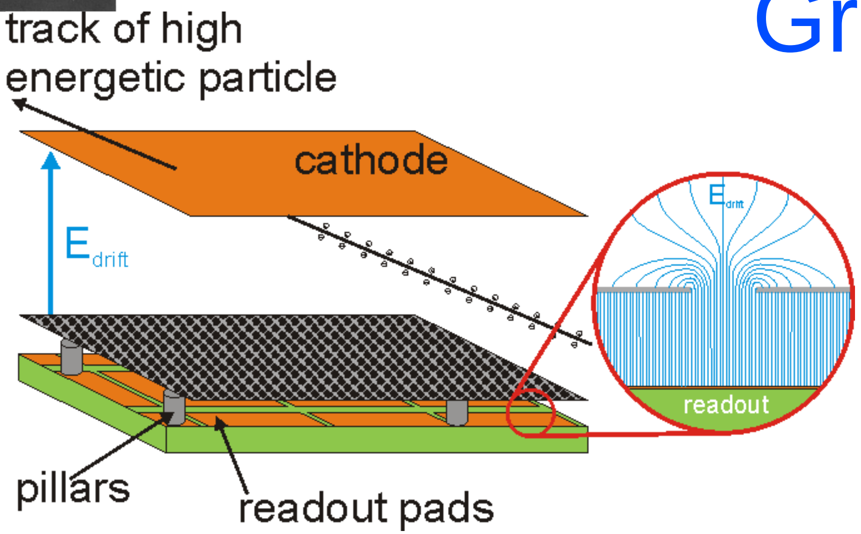


Pixel sizes of 55x55 µm² and 110x110 µm² performed very similar.
Pixel sizes of 220x220 µm² and 275x275 µm² had already significantly reduced performance.



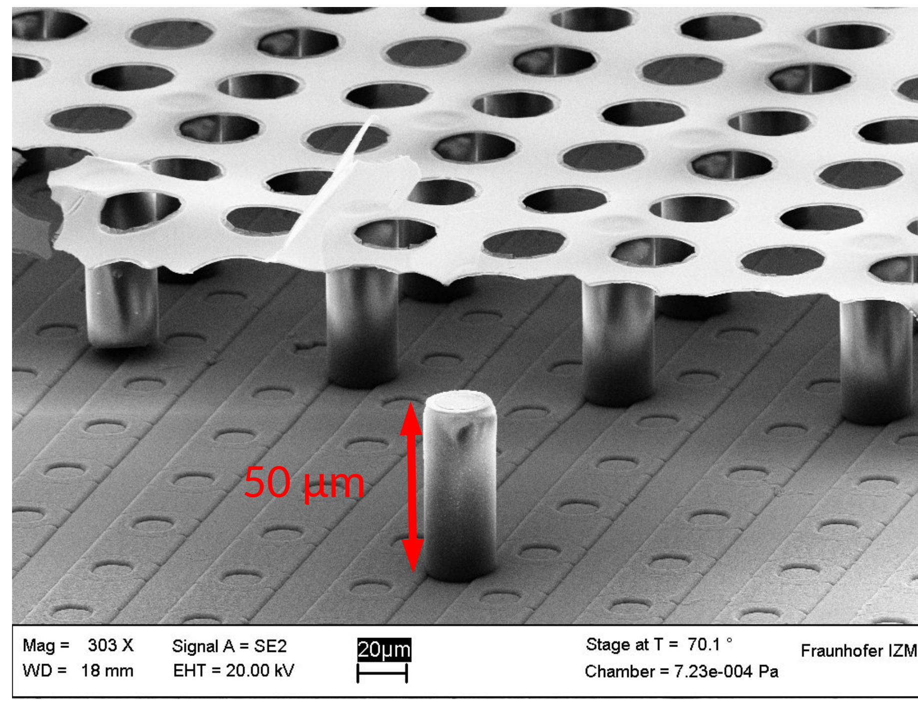
The Space-based Paradigm (V)
GridPix





Standard charge collection:
- Pads of several mm²
- Long strips (l~10 cm, pitch ~200 µm)

Instead: Bump bond pads are used as charge collection pads.



Could the spatial resolution of single electrons be improved?

$Ar:CO_2$ 80:20 → $D_T = 148\ \mu m/\sqrt{cm}$

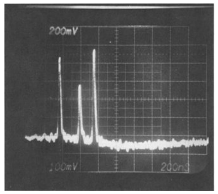
→ $\sigma = 11\ \mu m$

$Ar:iC_4H_{10}$ 95:5 → $D_T = 150\ \mu m/\sqrt{cm}$

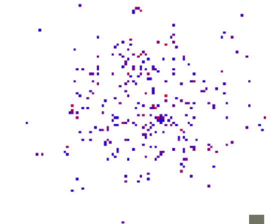
→ $\sigma = 11\ \mu m$

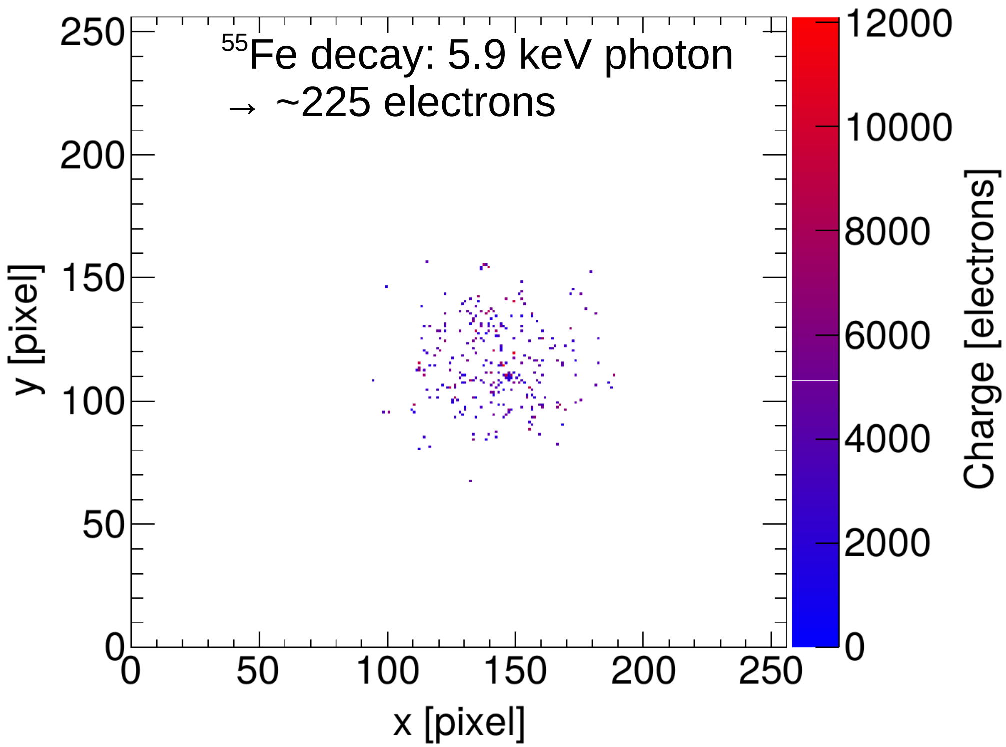
Smaller pads/pixels could result in better resolution!

At Nikhef the GridPix was invented.

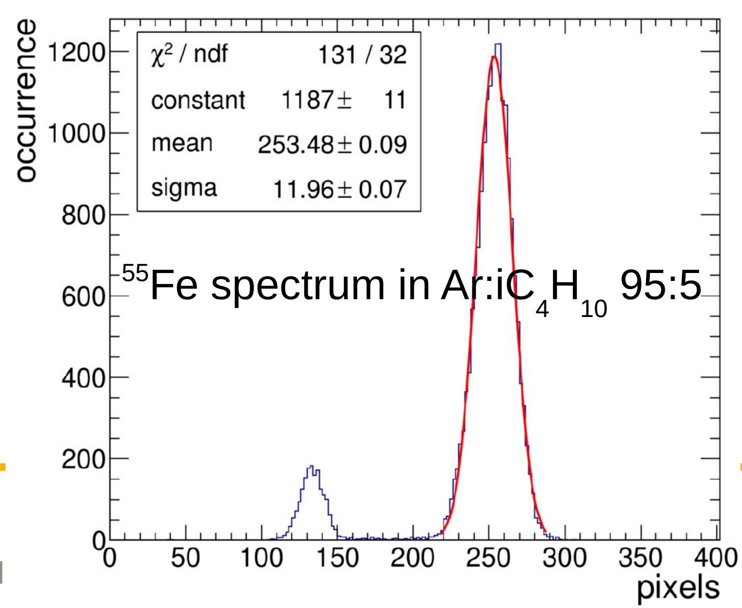


GridPix: Experiences with X-ray

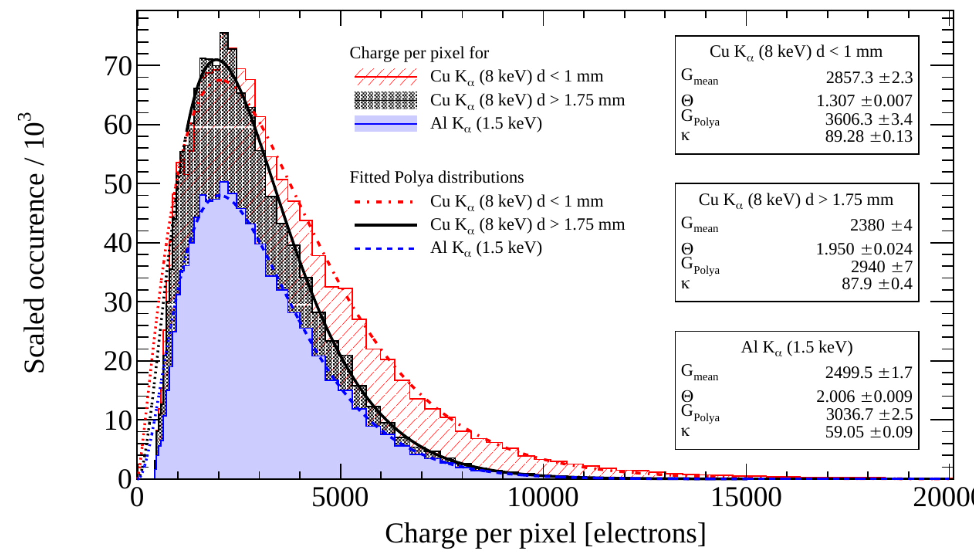




For CAST detailed studies with X-rays.
Cluster counting not possible, but
electron counting = pixel counting
→ high diffusion necessary
Detailed study with variable
X-ray source: NIMA 893 (2018) 26-34

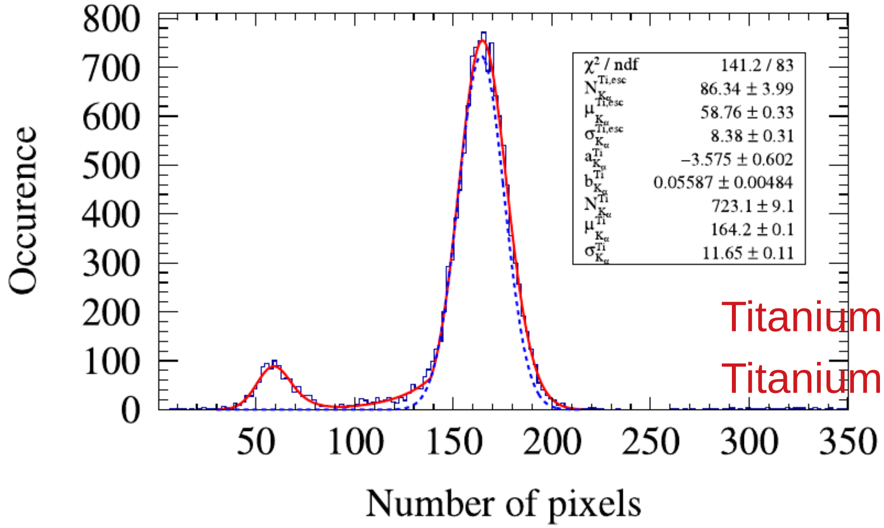


Single pixels show Polya distribution of gas gain

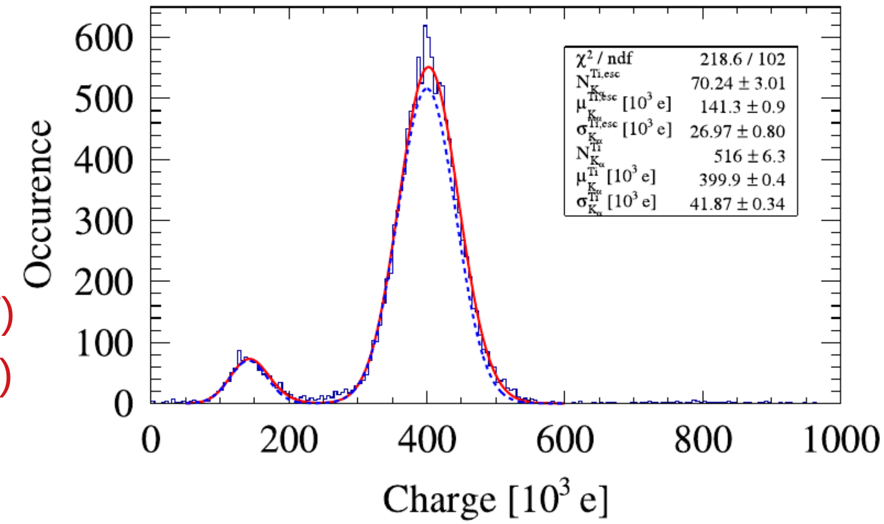


GridPix: Some X-ray Lines

Electron Counting

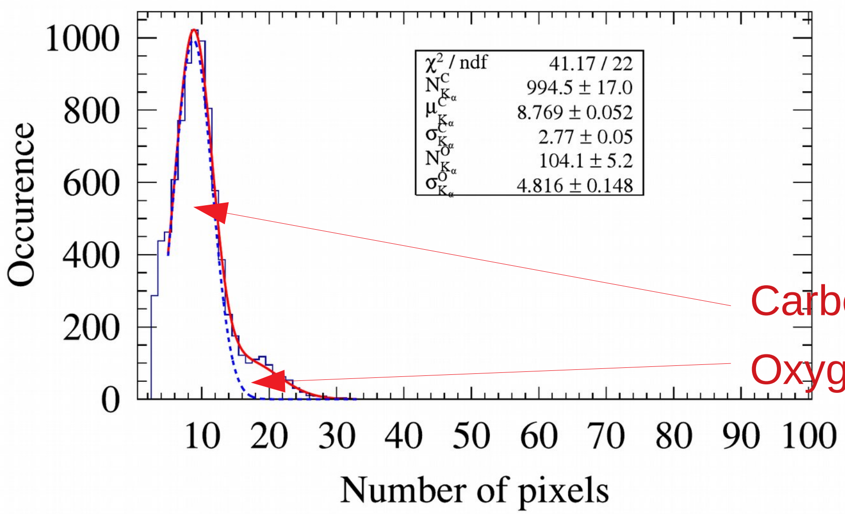


Charge Summation



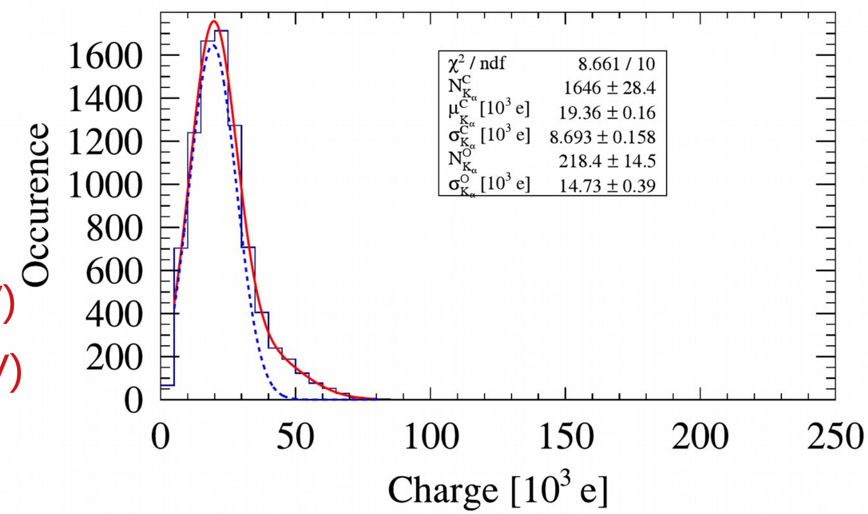
Titanium K_α (4510 eV)

Titanium K_β (4932 eV)

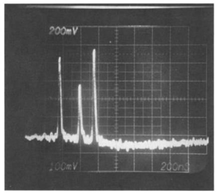


Carbon K_α (277 eV)

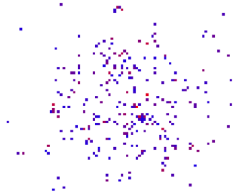
Oxygen K_α (525 eV)



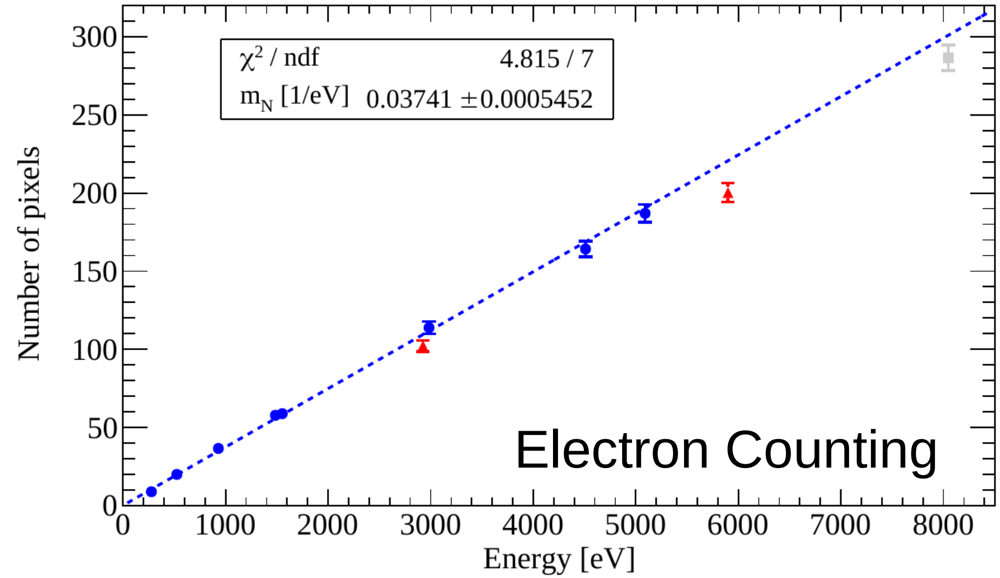
NIMA 893 (2018) 26-34

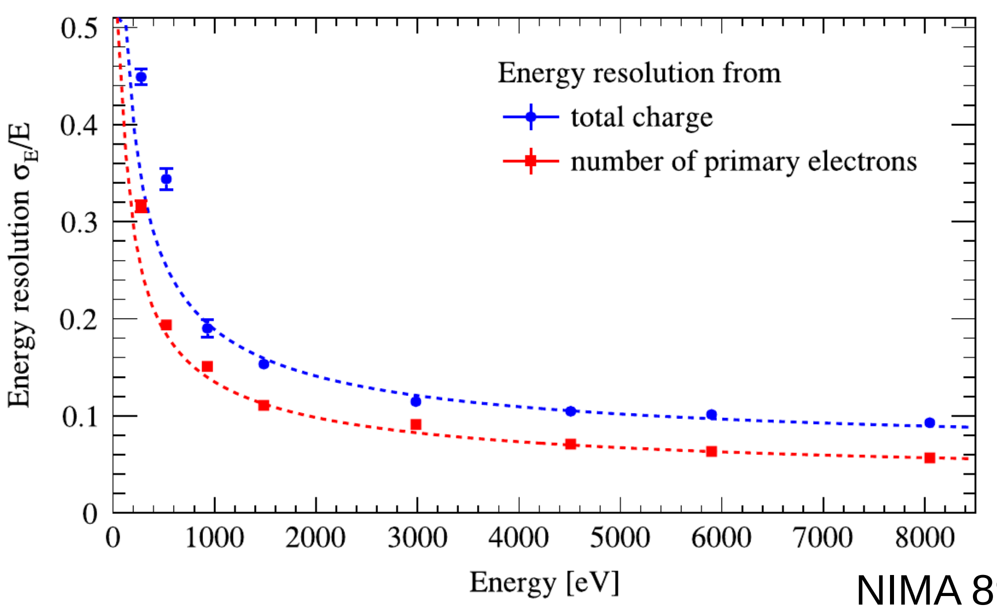


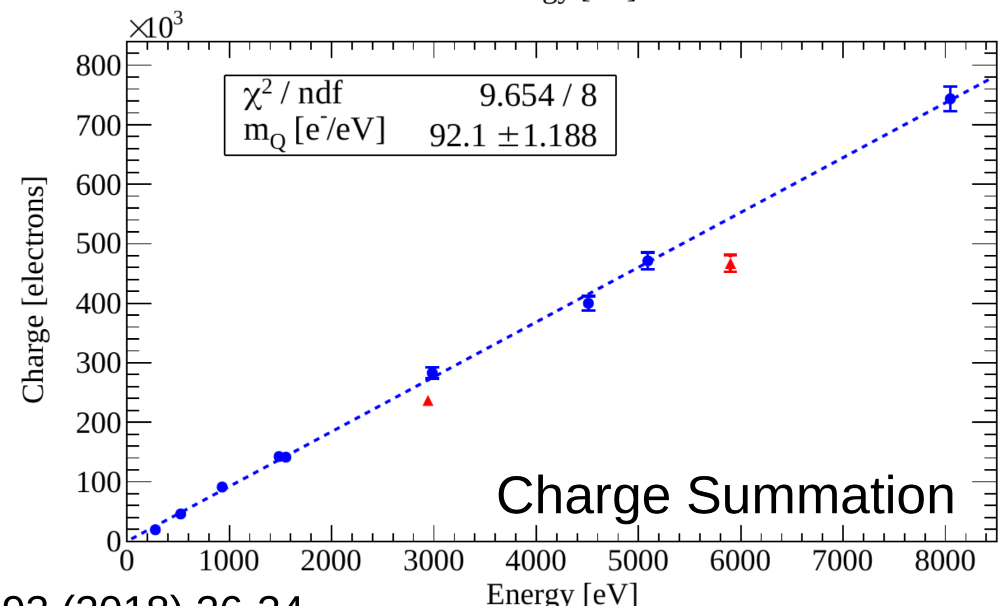
GridPix: Energy Resolution



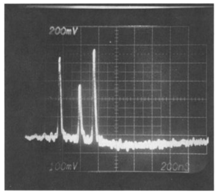
Pixel counting starts failing, if diffusion is not large enough and more than 1 electron ends upon a pixel.
Energy measurement based on collected charge still works fine.



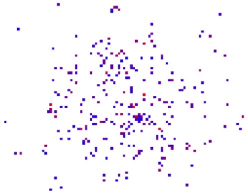


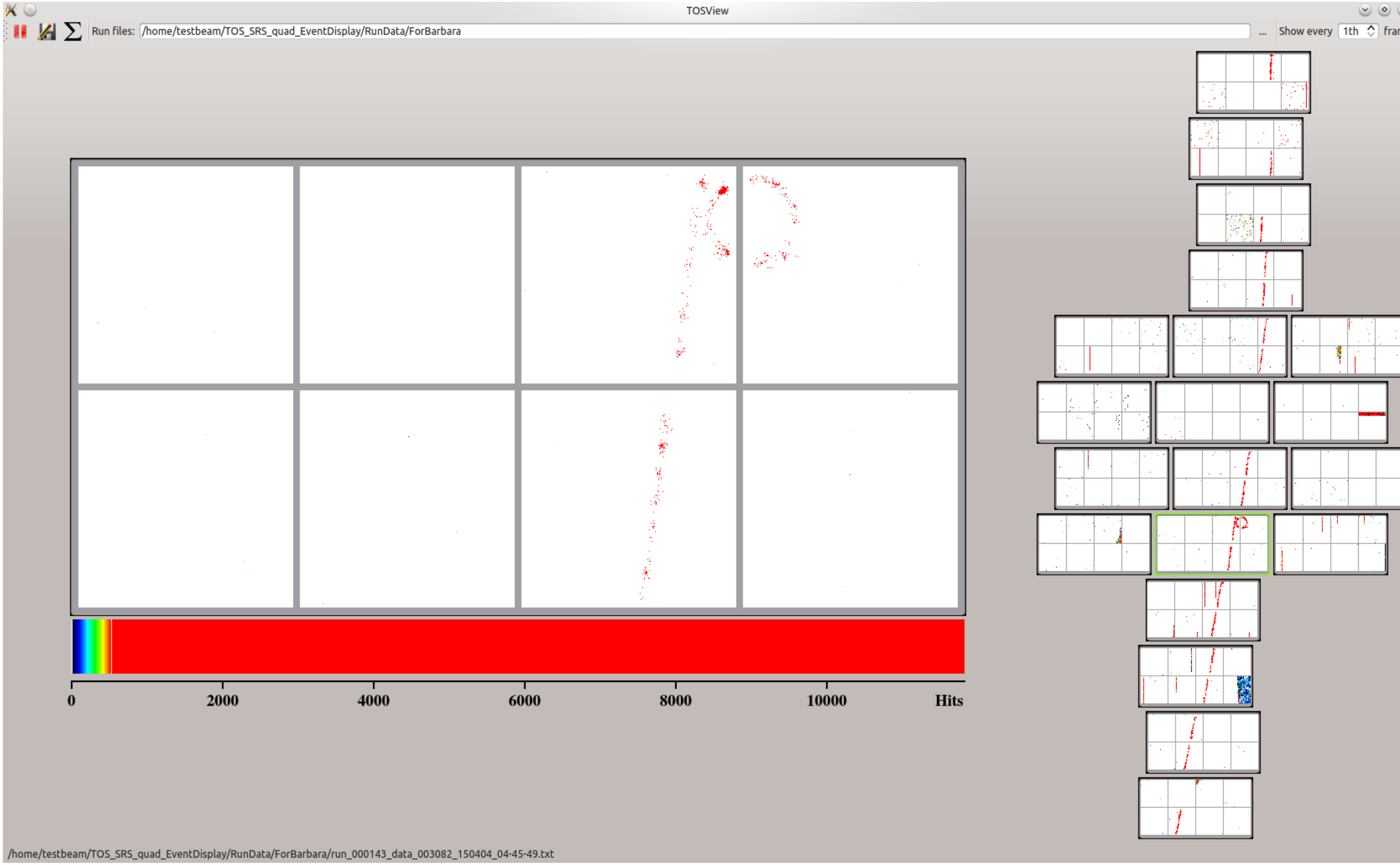


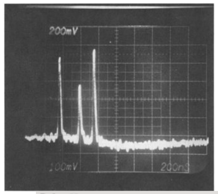
NIMA 893 (2018) 26-34



Event Picture of 5 GeV e-beam







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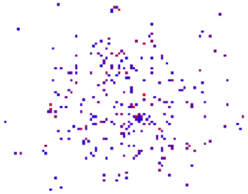
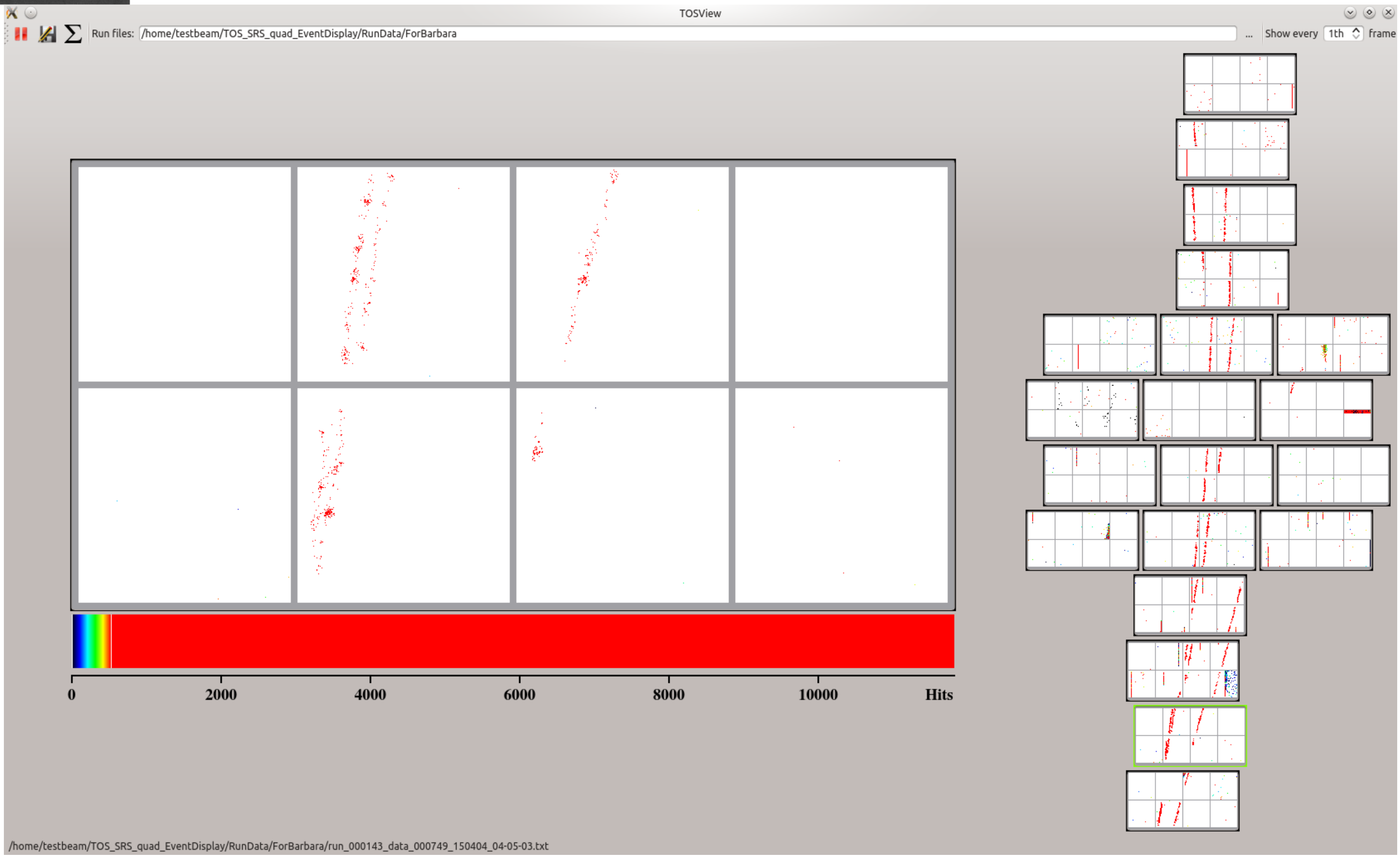
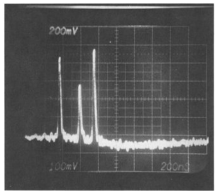
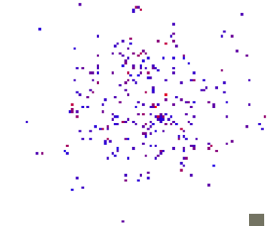
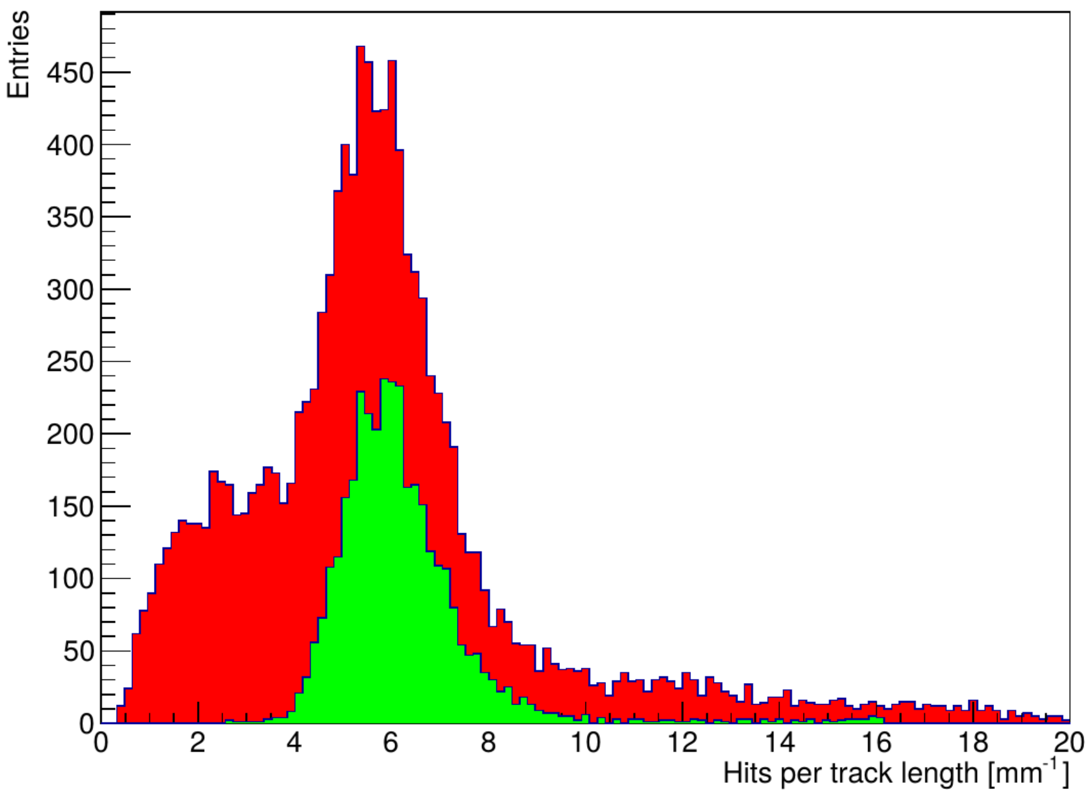






GridPix: dE/dx Measurements



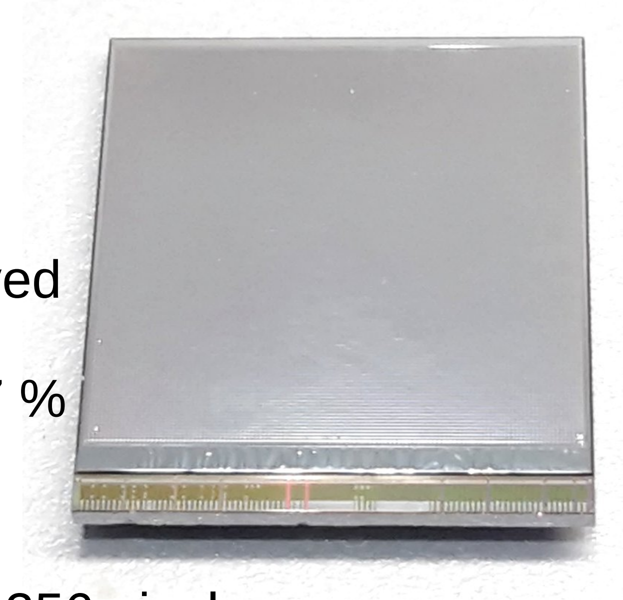


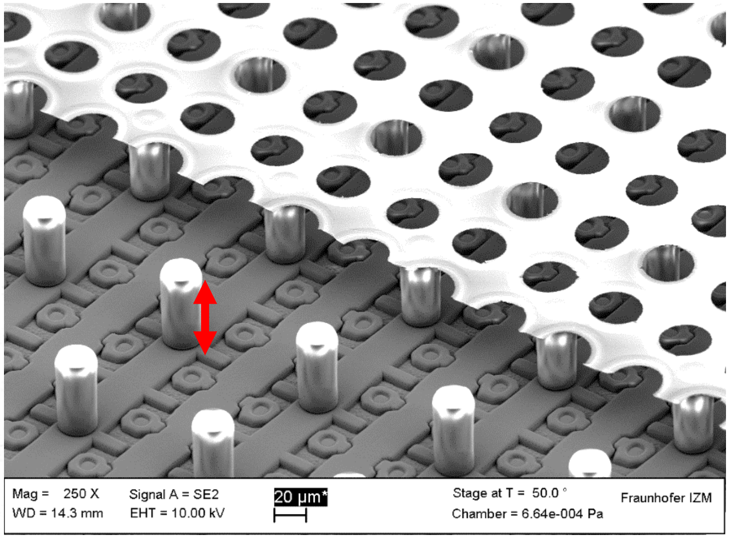
Measurement of primary electrons per mm:
$Ar:CF_4:iC_4H_{10}$ 95:3:2
B = 1 T
5 GeV electrons with a track length ~60 cm including gaps between GridPixes(!)
→ coverage of ~50-60 %
Using a truncated mean (central 90%) an energy resolution of 9.9 % was reached.
Extrapolation to ILD values gives 4.8 % with full coverage.

PhD thesis M. Lupberger

GridPix based on Timepix3

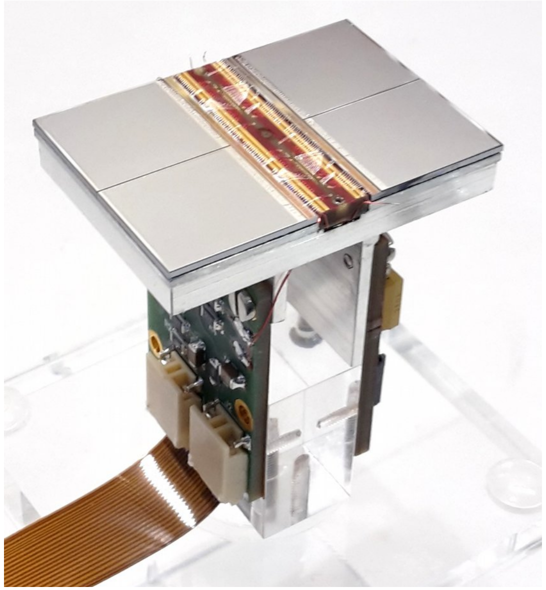
GridPix detectors have moved from Timepix to Timepix3 ASICs.
The grid layout was improved to have an active area in-crease from 91.3 % to 97.7 % of pixel matrix.

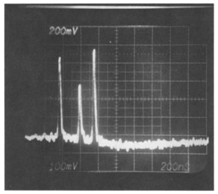




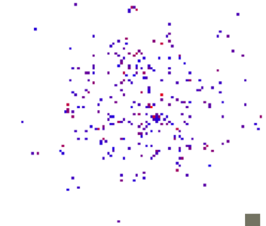
- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 µm²
- ENC: ~ 60 e^-
- Charge (ToT) and time (ToA) available for each hit
- Timing resolution: 1.56 ns for duration of ~410 µs
- Zero suppression on chip (sparse readout)
- Multi-hit capable (pixels sensitive after t_{ToT}+475 ns)

  Super-pixels store hits for some time
- Output rate up to 5.12 Gbps
- Power pulsing possible (800 ns for start up)





Data Analysis of GridPix with TP3

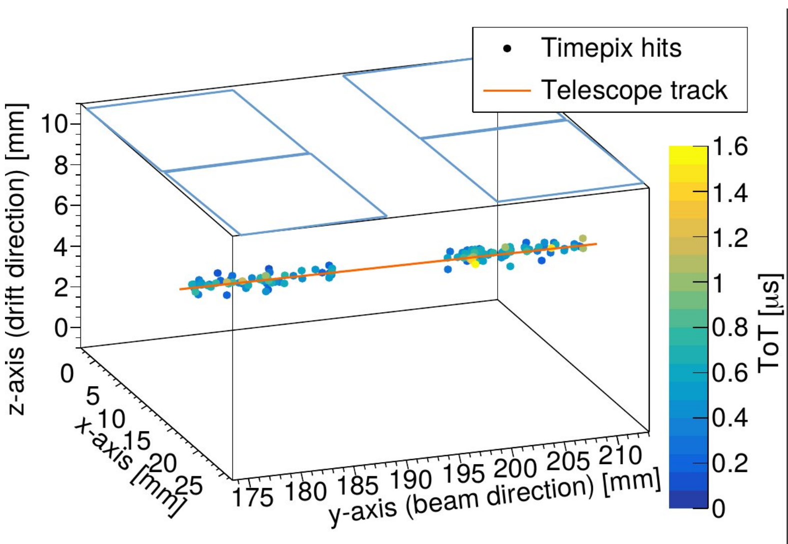


Test beams at ELSA accelerator at Bonn have been done with single GridPixes and QUADs.

Electrons with 2.5 GeV at a rate of 10 kHz

$Ar:CF_4:iC_4H_{10}$ 95:3:2

SPIDR read out



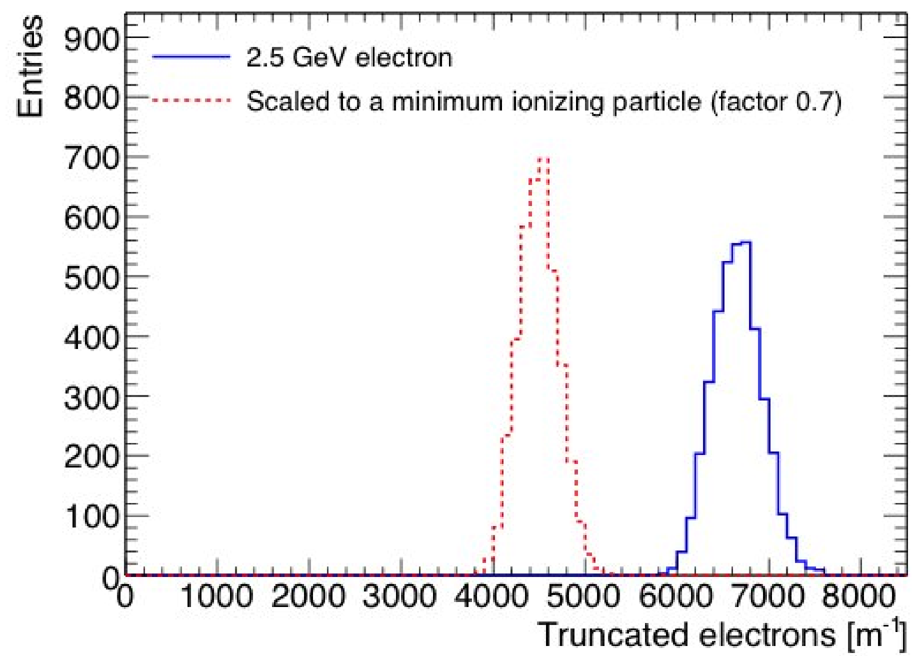
NIMA 908 (2018) 18-23

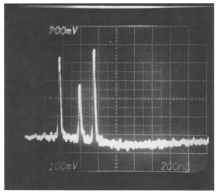
NIMA 956 (2019) 163331

Combining events → 1m track lengths were generated

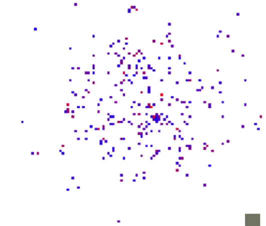
→ energy resolution 4.1 % with truncated mean.

→ extrapolation to MIP (x0.7 hits): energy resolution 4.9 %





Simulations & Extrapolation with Various Cluster Counting Algorithms



Geant4 MC data was tuned to correspond to test beam data, for which single chip events were added to get 1 m long tracks.

55 µm thick pixel rows

From hits projected along track:

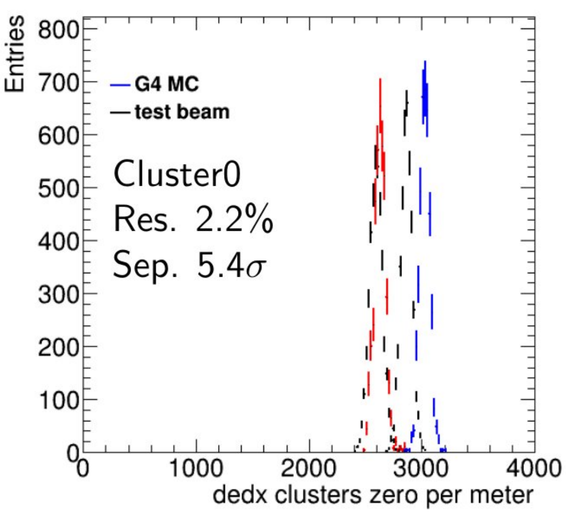
..	1	0	2	1	1	0	1	0	0	3	1	0	2	..

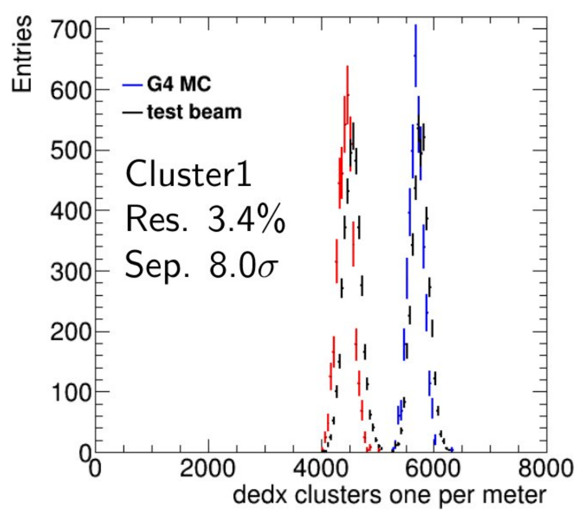
"Clusterz": Count number of clusters

..	1	0	1	0	0	0	1	0	0	1	0	0	1	..

"Cluster1": Count number of columns with hits

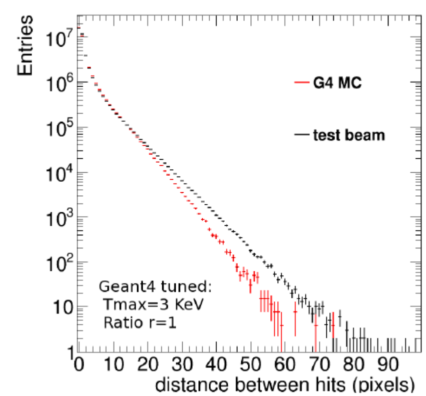
..	1	0	1	1	1	0	1	0	0	1	1	0	1	..

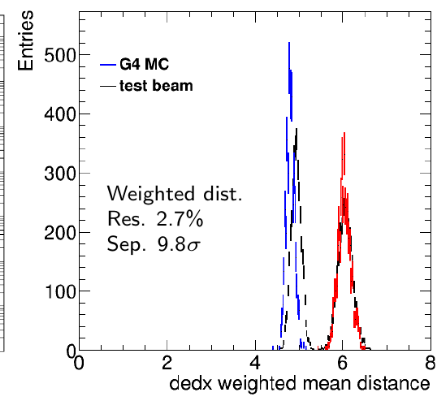




<u>Observation:</u> Distance between pixels varies more than expected from Poisson

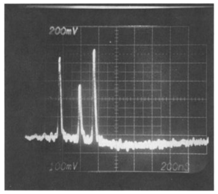
→ reweight these hits according to Poisson distribution



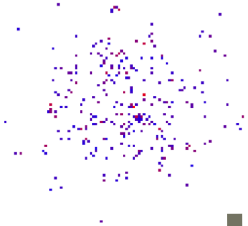


	Data		Monte Carlo	
Algorithm	Resolution	Separation	Resolution	Separation
Truncated Hits	4.1%	8.0σ	3.8%	7.1σ
Clusterz	2.2%	5.4σ	1.5%	8.7σ
Cluster1	3.4%	8.0σ	2.3%	9.5σ
Weighted distance	2.7%	9.8σ	2.5%	12.9σ

K. Ligtenberg at LCTPC-CM 3/2018



Readout Electronics



For Timepix and Timepix3 there is quite a variety of readout electronics.
They differ in specific performance parameters and should be chosen according to the envisioned application.
Here are some (certainly I have overlooked several):

Timepix:

- MUROS developed by Nikhef (deprecated?, relying on NI card)
- USB-device/FitPix developed by U. Prag,
- PRIAM developed by ESRF Grenoble
- DEMAS developed by IFEA Barcelona
- SRS developed by U. Bonn, open source, scalability to 160 ASICs proven

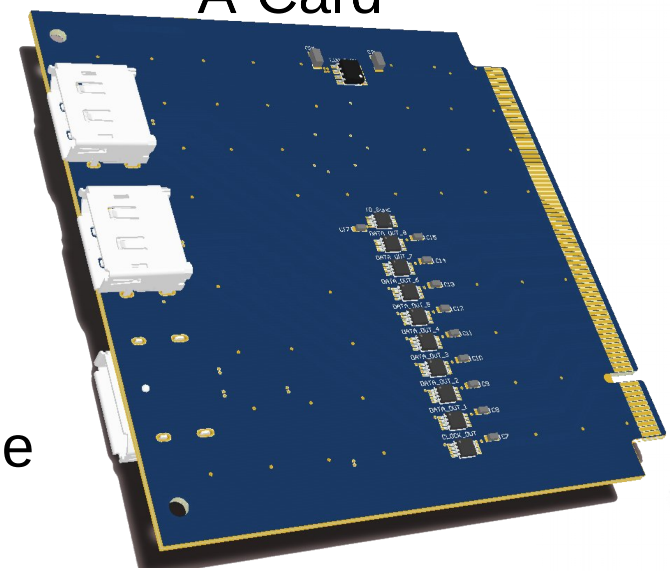
Timepix3:

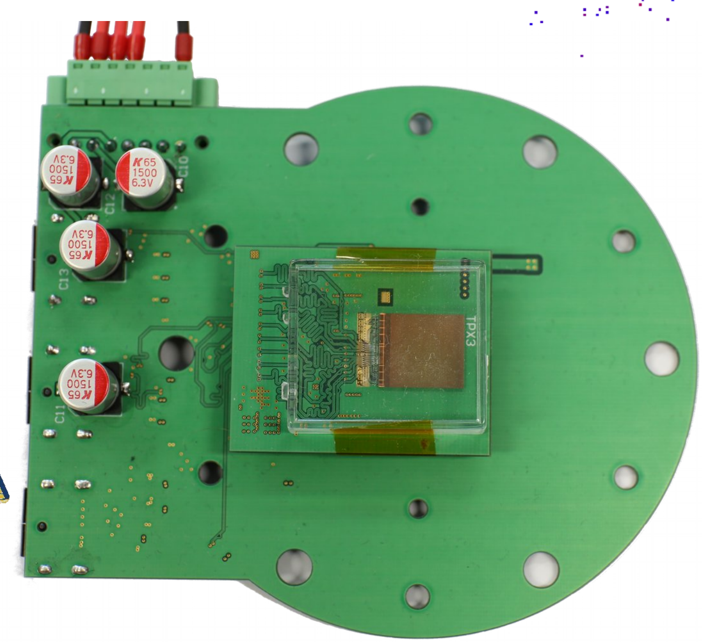
- SPIDR developed by Nikhef: 2015 JINST 10 C12028 / 2017 JINST 12 C02040
- USB 3.0 developed by Advacam: 2016 JINST 11 C12065
- Katherine developed by U.s. Prague: 2017 JINST 12 C11001
- SRS developed by U. Bonn: s. next slide.

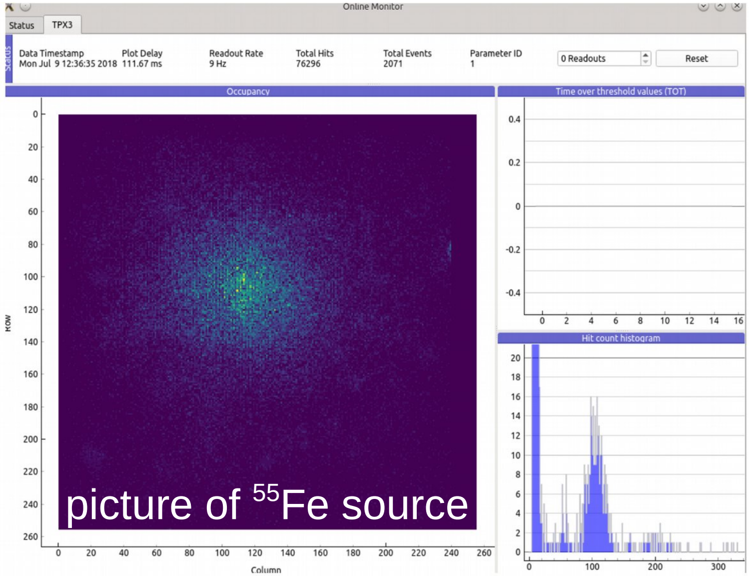
Timepix3 in SRS

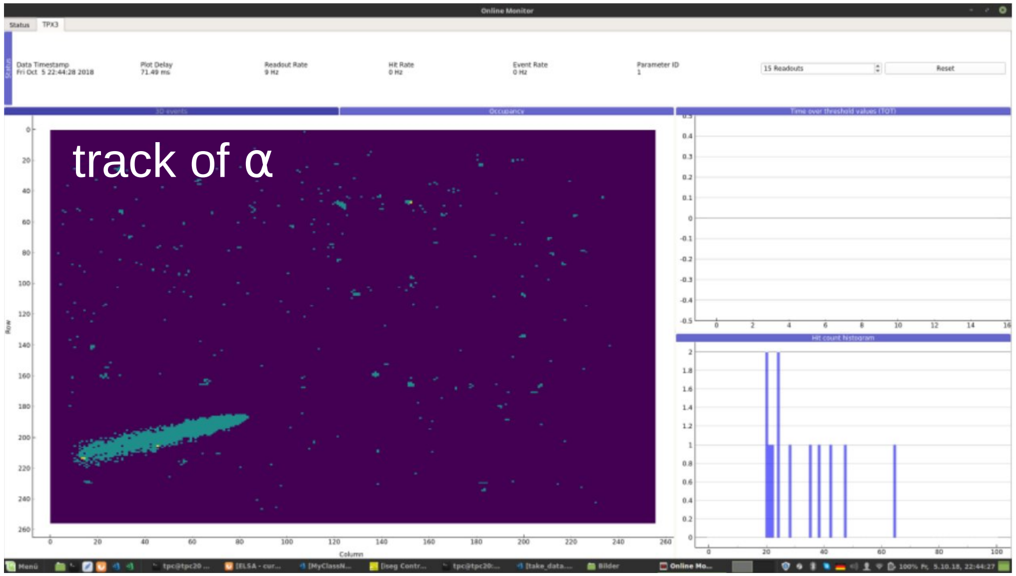
- Full functionality has been implemented
- Final tests and debugging is ongoing for a first code release
- Sofar only single chip
- Update for mutli-chip use (8 chips / FEC) soon

A-Card









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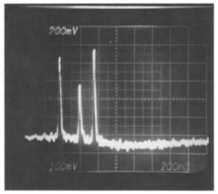
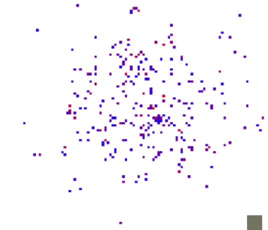


Conclusion



Cluster counting has been around for ~40 years.

There are two approaches:

1.) The time-based paradigm uses drift chambers of small radii (O(5-10mm))
Tracks entering perpendicular to the wire
Status: Several successful test beam demonstrators
Electronics mostly custom made with very high bandwidth amplifiers (> 100MHz)

2.) The space-based paradigm uses
Tracks enter parallel to the readout (e.g. TPC)
Status: Some theoretical considerations and simulations
Electronics is based on high resolution pixel readout ASICs (Timepix / Timepix3)
MPGD friendly, but best choice probably is due to other considerations of tracker
My guesses:
Possibly better for higher rate experiments.
Best choice of gas amplification stage: GridPix

Alternative approach for longer drift distances:
- electron counting instead of cluster counting → eliminates Polya of gas amplification
- negative ion TPC reduces the spatial diffusion and has very low drift velocity
→ both space and time-based approach possible (with Timepix 3)