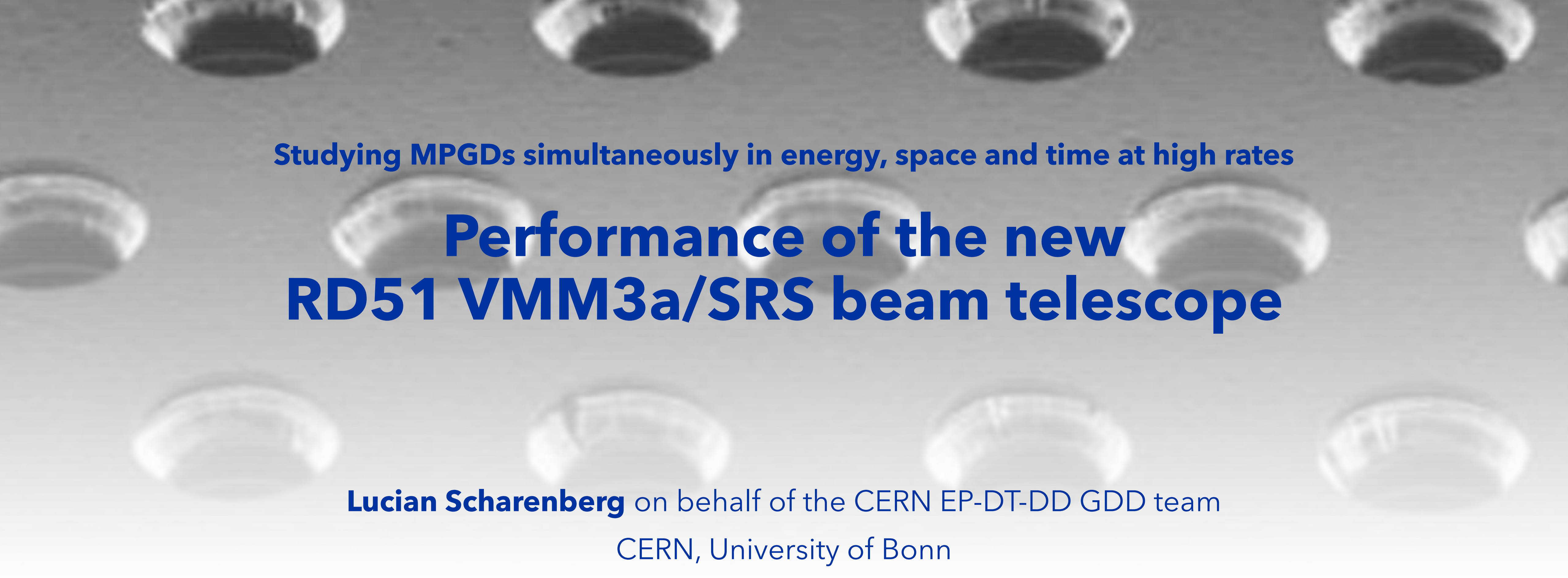

Studying MPGDs simultaneously in energy, space and time at high rates

Performance of the new RD51 VMM3a/SRS beam telescope

Lucian Scharenberg on behalf of the CERN EP-DT-DD GDD team

CERN, University of Bonn

7th International Conference on Micro-Pattern Gaseous Detectors

16 December 2022

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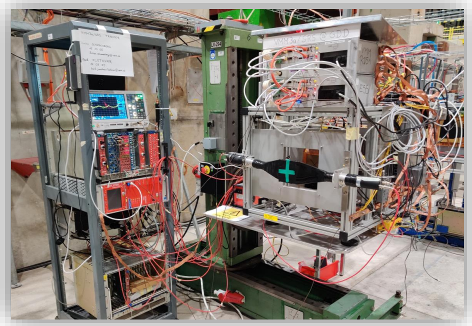
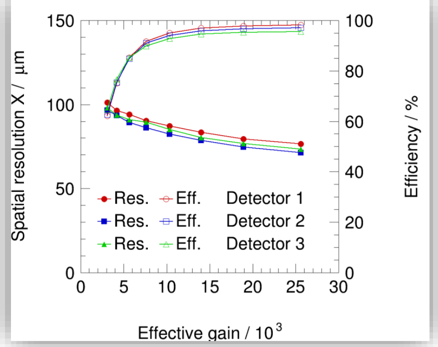
Outline

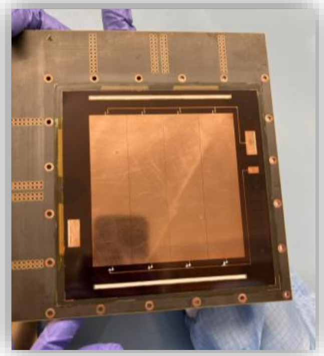
Overview



Telescope’s performance



Detectors under test



Operation at NA61

Motivation

- Common **RD51** electronics developments: **Scalable Readout System (SRS)**
- Successful integration of **ATLAS/BNL VMM3a** front-end ASIC to enhance SRS' performance
- Profit from the electronics capabilities in the RD51 test beam campaigns at the CERN SPS

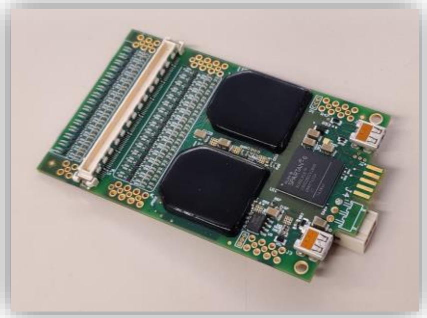
- Goal: **build new beam telescope**
    - **Higher rate capability** than so far
    - Handle many different detector technologies and sizes
- Commission new electronics, using well established detector technologies (triple-GEM)

[1] NIM A **1031** (2022) 166548
[2] IEEE TNS **69** (2022) 976-985
[3] https://vmm-srs.docs.cern.ch/
[4] Control software

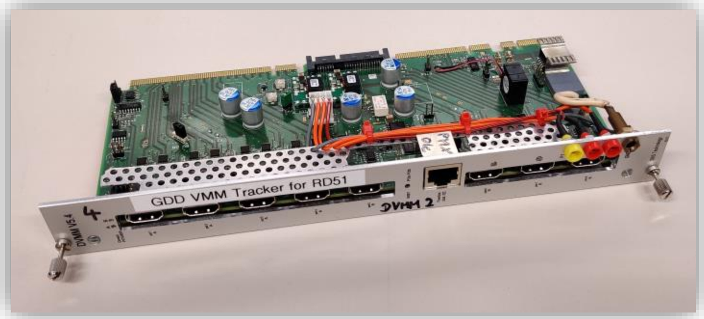
Readout electronics

- **RD51 Scalable Readout System** (SRS) with its **VMM3a** front-end
  → Scalability to read out **multiple detectors at once**
- ATLAS/BNL VMM3a
  - **Charge** ADC (10-bit, effectively 8-bit) **and time** (~ 1 ns resolution) **simultaneously**
  - Adjustable settings (peaking times 25 to 200 ns, gain 0.5 to 16 mV/fC)
  - Input capacitances < 200 pF to 2 nF
  - **Self-triggered @ THL** (no external trigger signal)
  - **Continuous readout**
- Consequences on system operation (changes of paradigm)
  1. **Common clock and synchronisation required**
     → Cluster reco. or event building based on time
  2. **Each signal above THL will be processed and acquired**
     → Higher THL required than normal (based on hit rate)
     → So far achieved: **0.5 fC** (lab)**, 1.3 fC to 1.7 fC** (test beam)

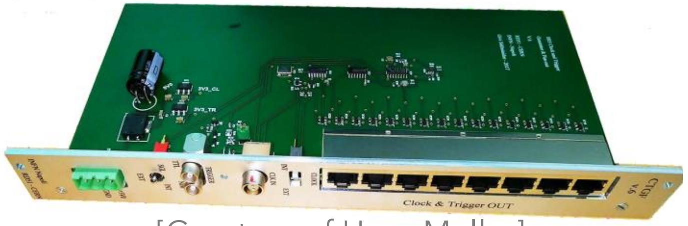
RD51 VMM hybrid



Digital VMM adapter (DVMM) card



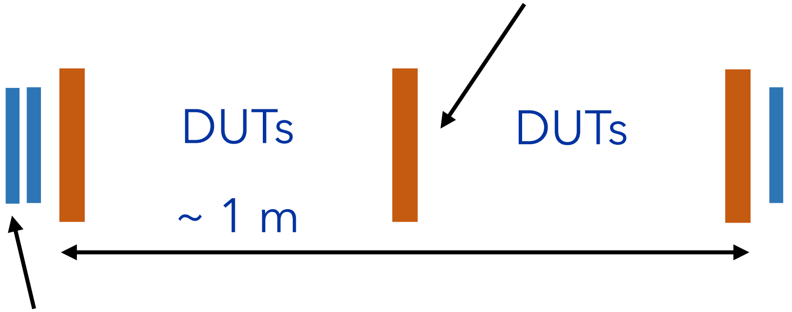
Clock and Trigger Fanout (CTF) card



[Courtesy of Hans Muller]

Structure of the beam telescope

- **3 COMPASS-like triple-GEM detectors**
  → Ar/CO_2 (70/30 %)
  → 256 + 256 x-y-strip readout

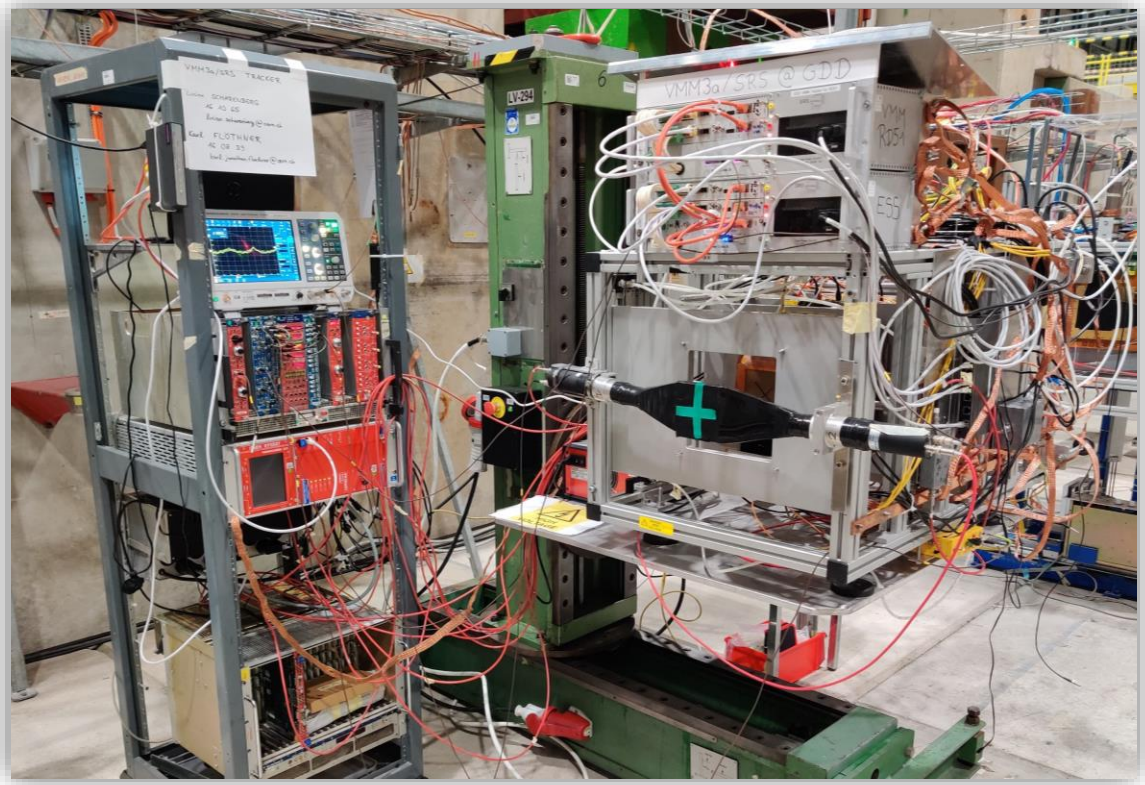


DUTs

DUTs

~ 1 m

- 3 Scintillators/PMT with NIM coincidence
  → **Read out via the RD51 VMM hybrid**
- **More than 2k channels for DUTs**



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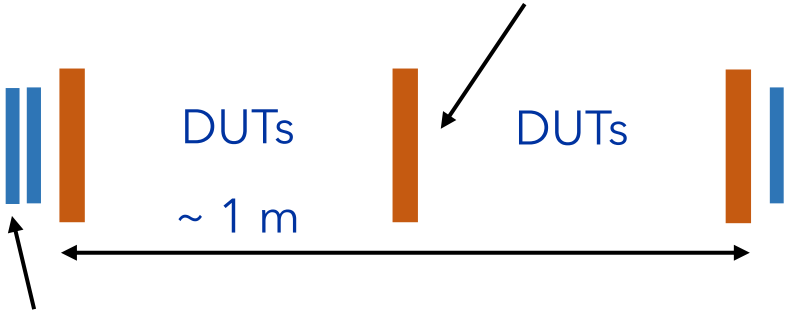

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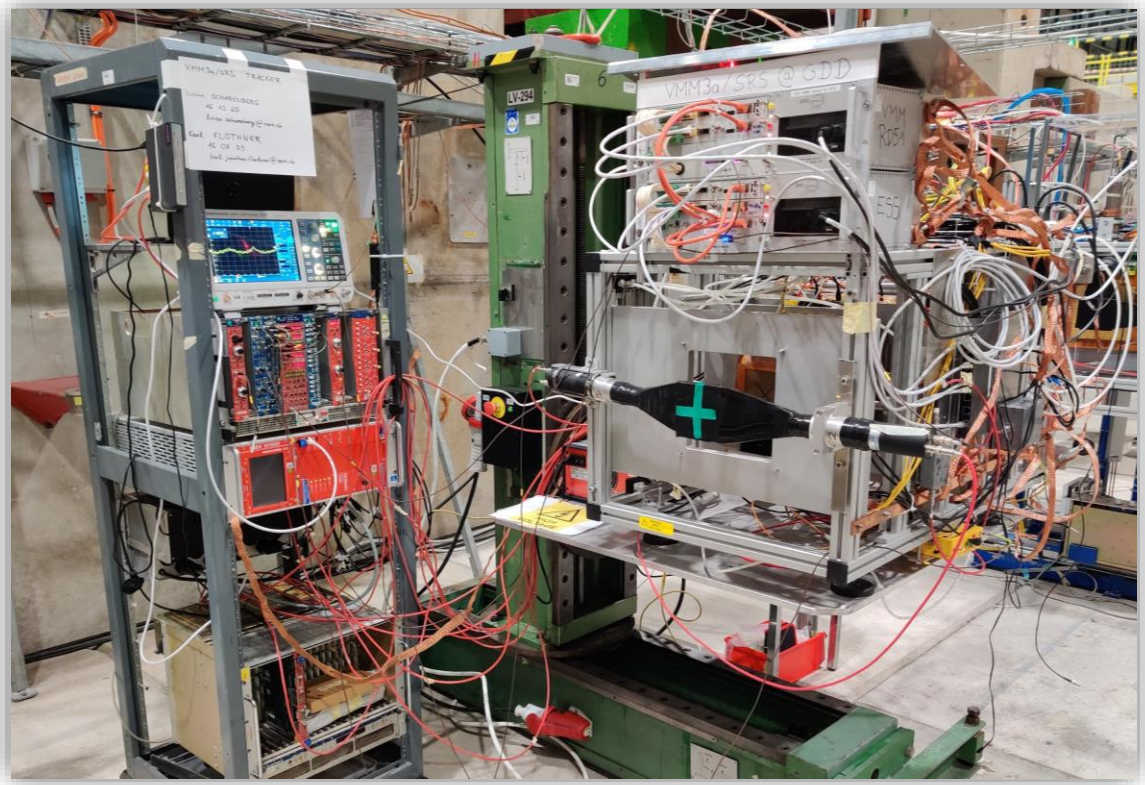
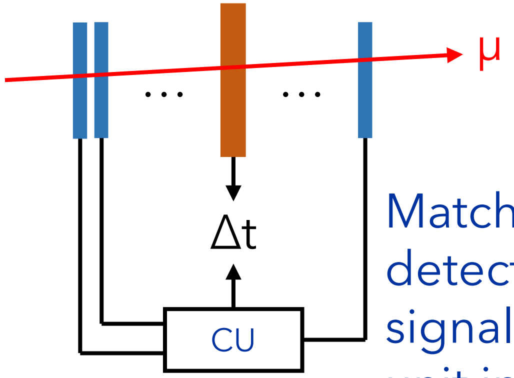


Characterise the performance of the beam telescope's components

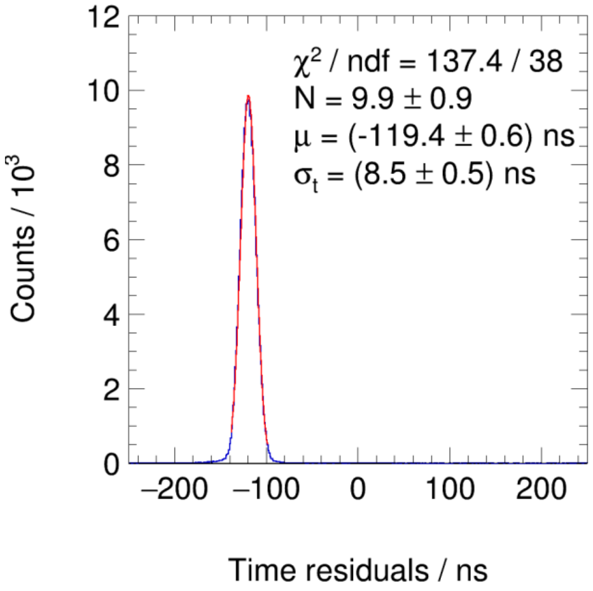
[1] vmm-sdat

Beam telescope's performance:
Detector-based studies

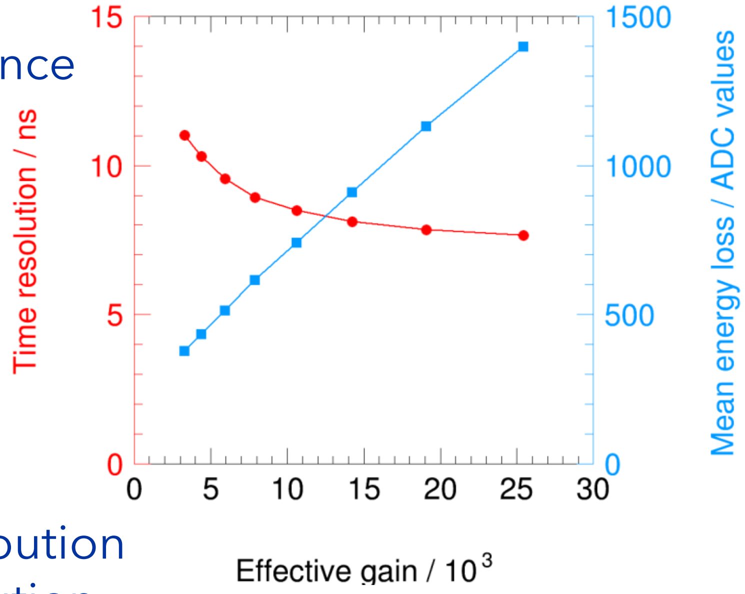


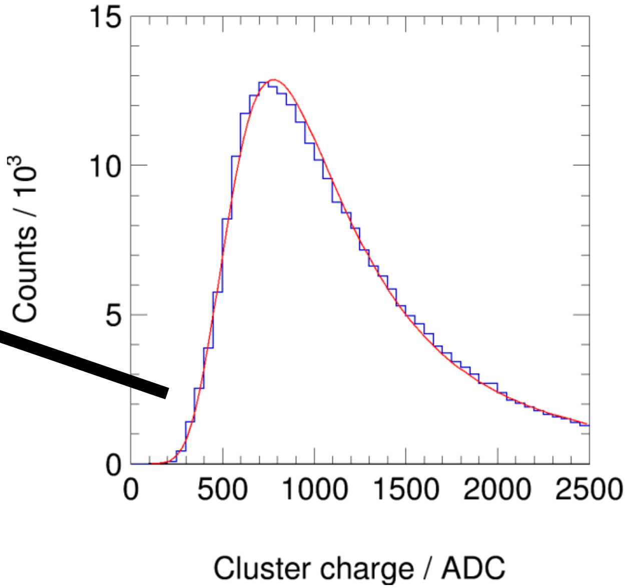
Cluster reconstruction per RO-plane/detector via hit time, using *vmm-sdat* [1]

Match clusters from detector with NIM signals from coincidence unit in time



Width of time difference distribution gives time resolution



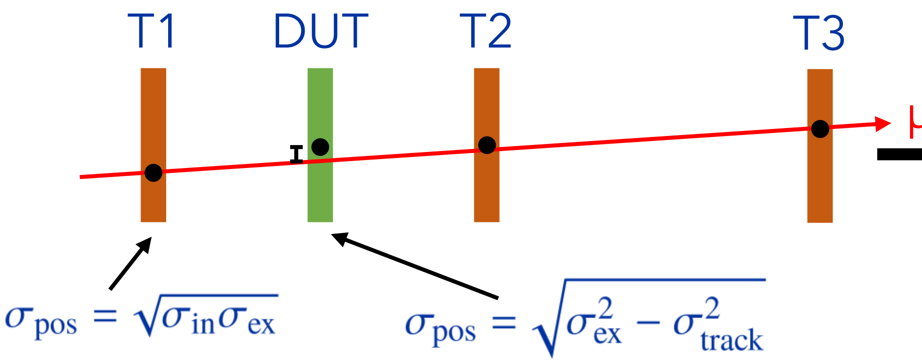


Simultaneously, other information from clusters with matching time provided

[1] anamicom
[2] J. Bortfeldt (PhD thesis)
[3] NIM A **538** (2004) 372-383
[4] S. Horvat (PhD thesis)

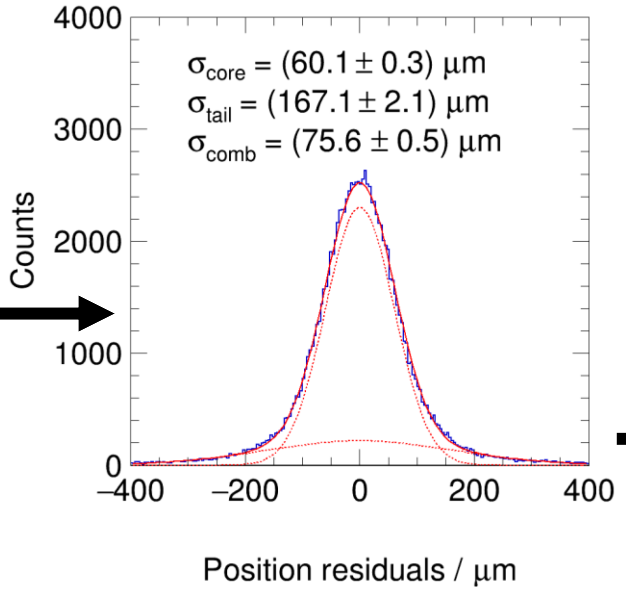
Beam telescope's performance:
Track-based studies

- Position determination: **Centre-of-gravity (COG)**
- Event-building based on cluster time
- Tracking with **Kalman filter** via *anamicom* [1]
- **Spatial resolution studies** as in [2]
- Tracking error as in [4]

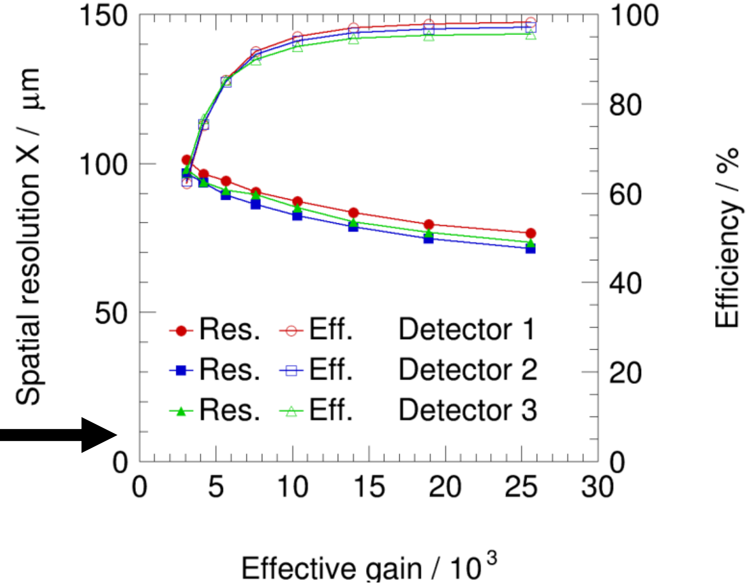


$\sigma_{\text{pos}} = \sqrt{\sigma_{\text{in}}\sigma_{\text{ex}}}$

$\sigma_{\text{pos}} = \sqrt{\sigma_{\text{ex}}^2 - \sigma_{\text{track}}^2}$



Efficiency not @ 100%
due to geometrical effects and
non-working readout channels

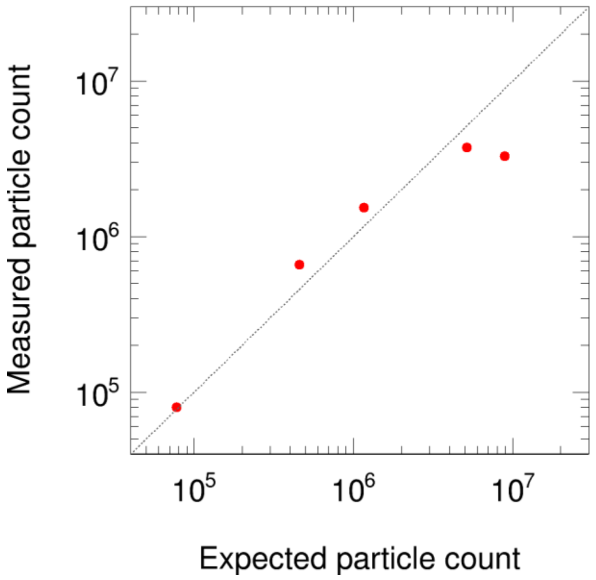


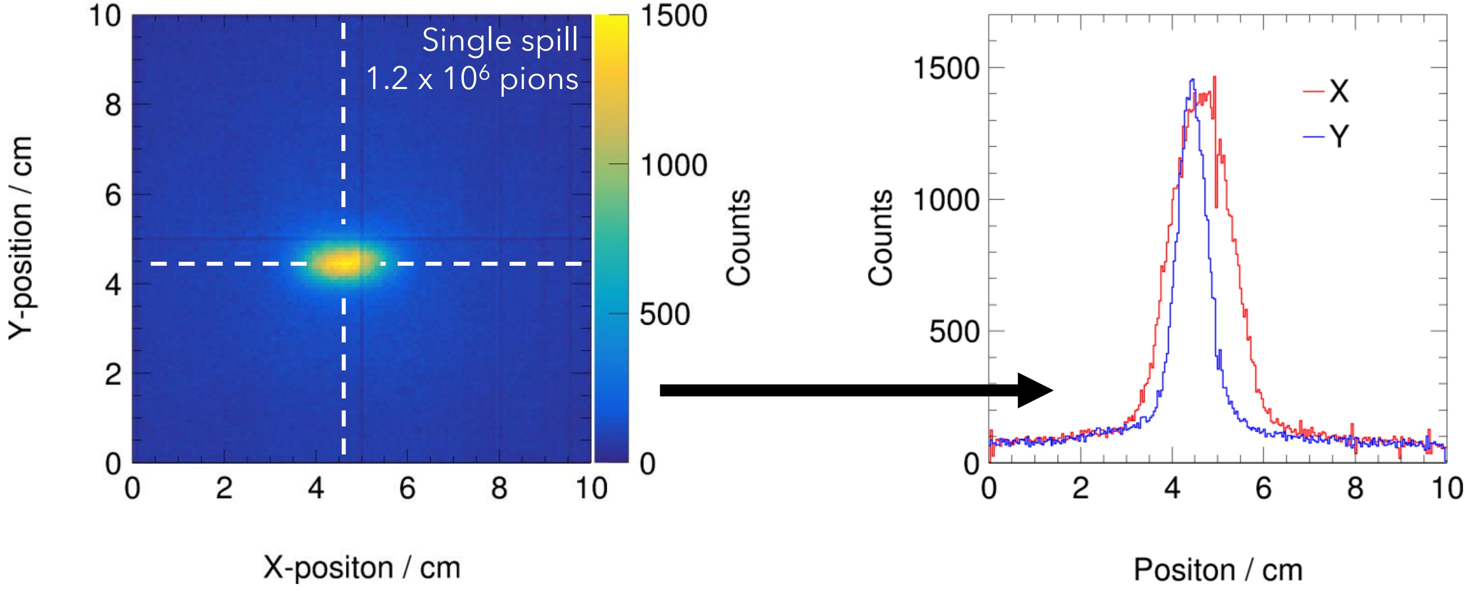
~10 kHz recorded interaction rate

- Efficiency $\epsilon = \frac{N_{\text{matched}}}{N_{\text{total}}}$

[1] NIM A **1031** (2022) 166548

Beam telescope's performance:
Rate-capability





- 80 GeV/c pion beam: particle flux from ~7 x 10^4 particles per spill (~5 s) to 10^7 particles per spill
- Until **~1.5 x 10^6 particles per spill** each particle interaction can be recorded
- **Bandwidth saturation** with ~5 x 10^6 particles per spill and more
  - → Loss in number of recorded interactions
  - → Decrease of quality of acquired data, as described in [1]

[1] NIM A **1011** (2021) 165576

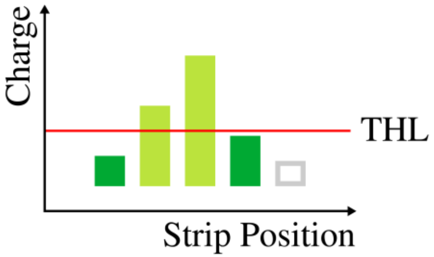
Improving the spatial resolution

- Position determination: **Centre-of-gravity (COG)**
- With **X-rays** [1]: **improvement of position reconstruction** for imaging applications by
  - Modification of COG (**Q² weighting**)

$$x = \frac{\sum_i Q_i^n x_i}{\sum_i Q_i^n} \qquad n = 2$$

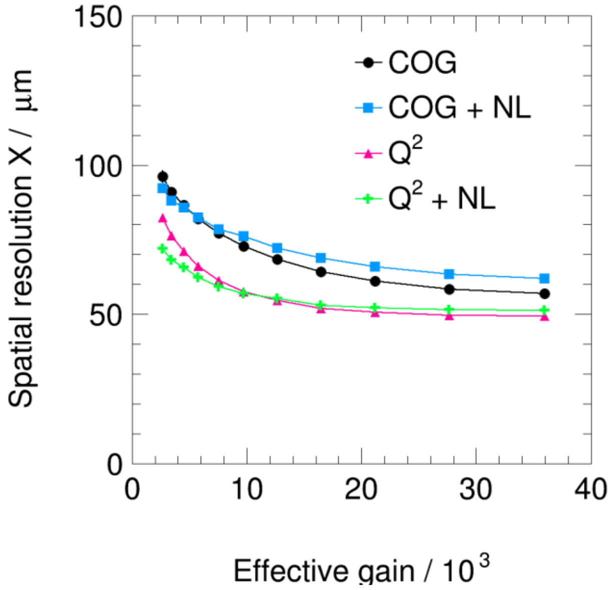
Review of COG systematics and modifications:
Igor Smirnov: *Algebraic methods for reconstruction of coordinates in strip detectors*

  - VMM3a: **neighbouring-logic** to recover charge below THL



- Cross-check for MIPs with beam telescope (reference position)

Example @ 1.5 fC THL



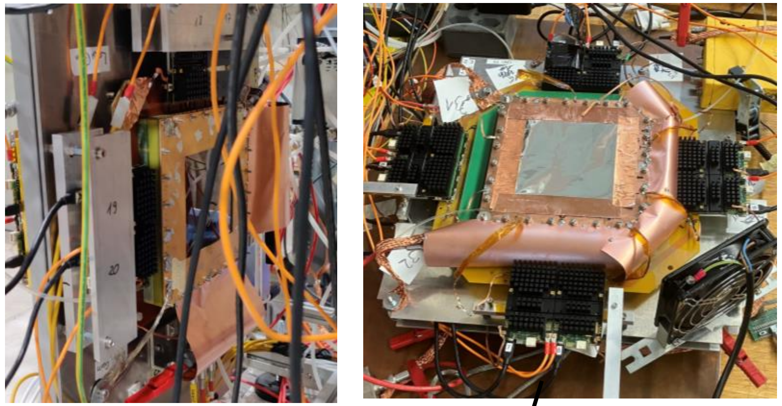
Scanned: THL range from 1.5 fC to 5.5 fC
- **Q² improves spatial resolution all the time**
- NL only at low signal-to-threshold ratio

Detectors under test

Triple-GEM

Finer hole pitch
(90 µm vs 140 µm)
→ stability
→ spatial resol.

Three layer **XYU readout** board
→ ambiguity free readout
→ spatial resol.

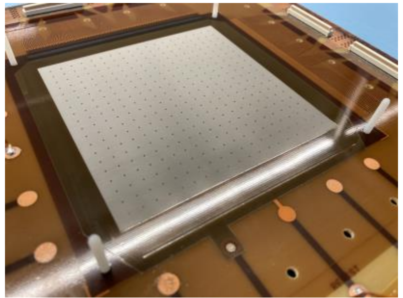


[Courtesy of Karl Flöthner]

K. Flöthner: *The novel XYU-GEM for ambiguity reduced tracking*

Resistive-plane MicroMegas

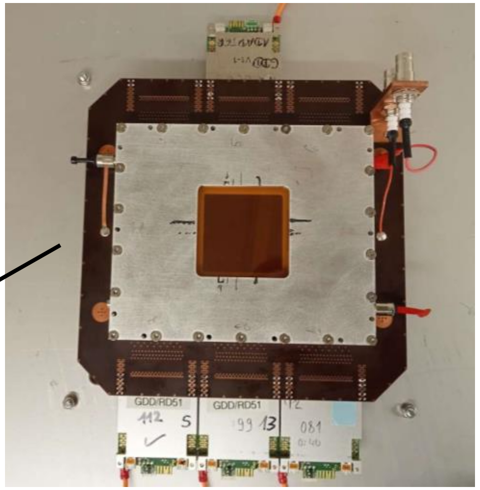
Thin-mesh MM
→ stability
→ higher gain



[Courtesy of Djunes Janssens]

Small-pad MM
→ benchmark XYU readout

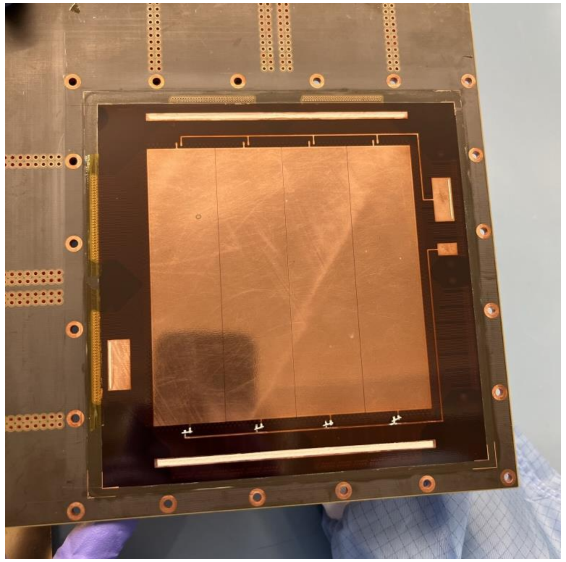
M. Iodice: *Towards Large Size Pixelized Micromegas for operation beyond 1 MHz/cm²*



[Courtesy of Maria Teresa Camerlingo]

micro-resistive WELL

µRWELL
→ low material budget
→ replacement of triple-GEM detectors in beam telescope



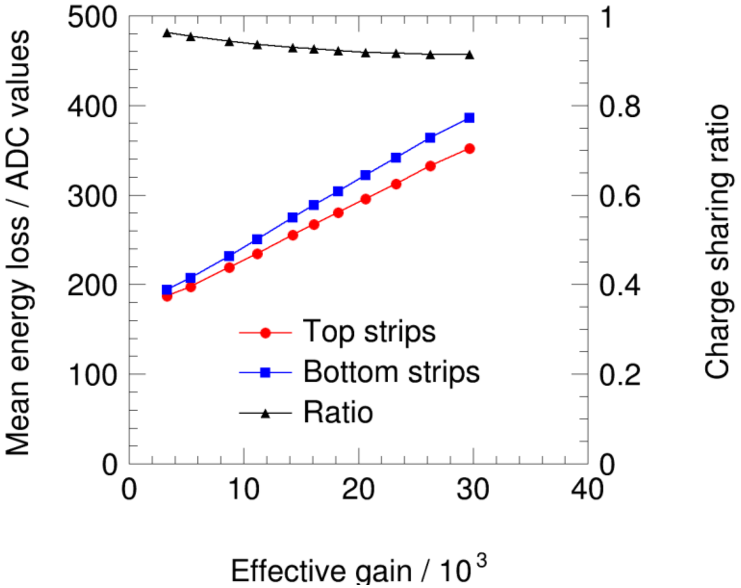
[Courtesy of Djunes Janssens]

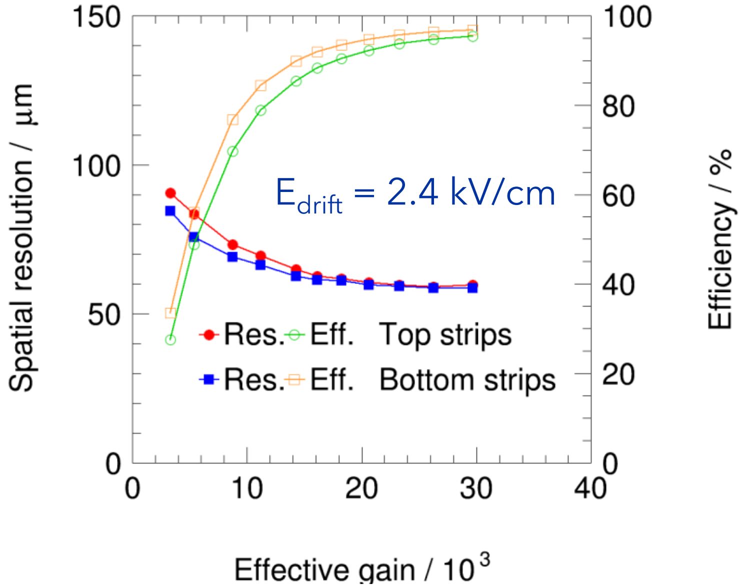
[1] Yi Zhou et al. (RD51 Coll. Meet.)

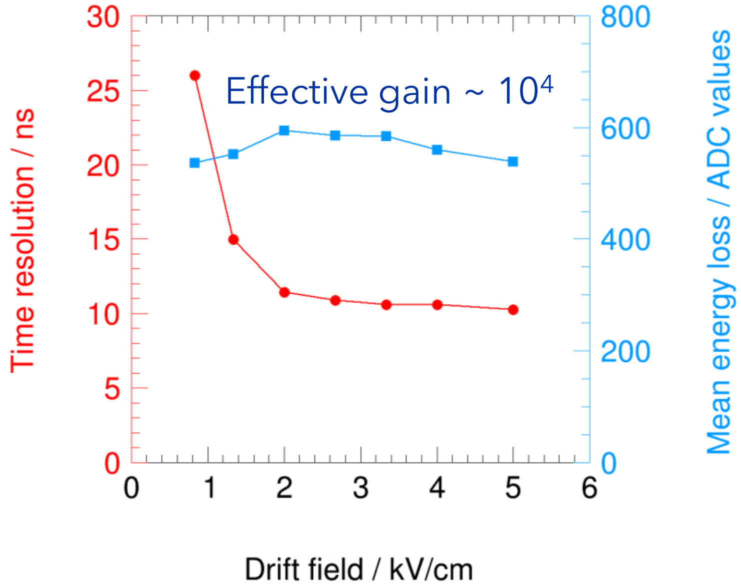
Preliminary

Studies on the micro-resistive WELL

- μRWELL **lent by Yi Zhou and Xu Wang from USTC** [1]
- 10 x 10 cm², 256+256 x-y-strips, 400 μm pitch, 3 mm drift gap, Ar/CO_2 (70/30 %), 40 MΩ/□
- **Optimised for equal charge sharing between top and bottom strips**
- Not optimised for high-rate operation

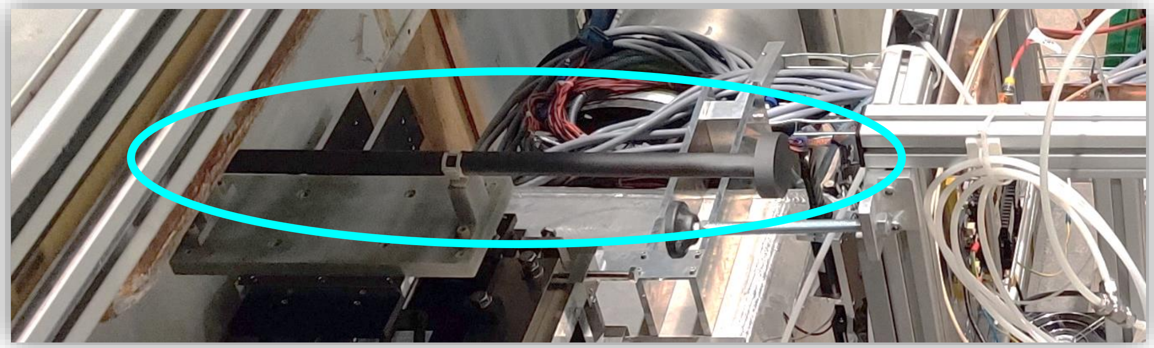






The NA61/SHINE experiment

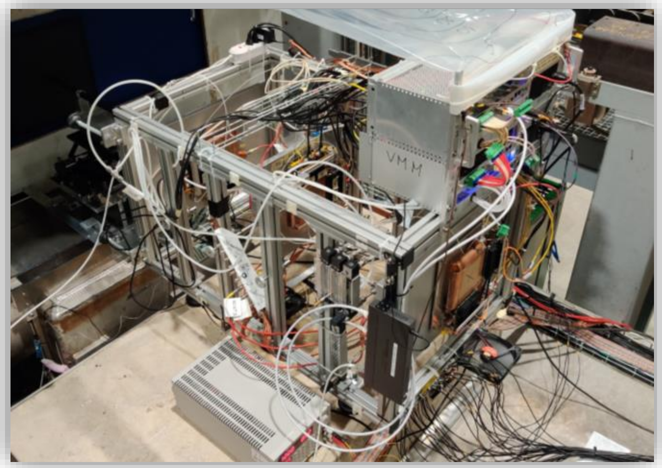
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment (SHINE)
  - Strong interactions (**heavy ion collisions**):
    → Phases of strongly interacting matter
    → **Onset of deconfinement**
  - Interactions of cosmic rays in the interstellar medium (**light ion collisions**): Pierre Auger Observatory, **AMS**, …
  - Study of **target interactions** for neutrino experiments: J-PARC (**T2K**), Fermilab (**DUNE @ LBNF**), …
- **Here: T2K run** (T2K replica target: ~1 m carbon rod)
  → Reduce uncertainties in neutrino oscillation experiments

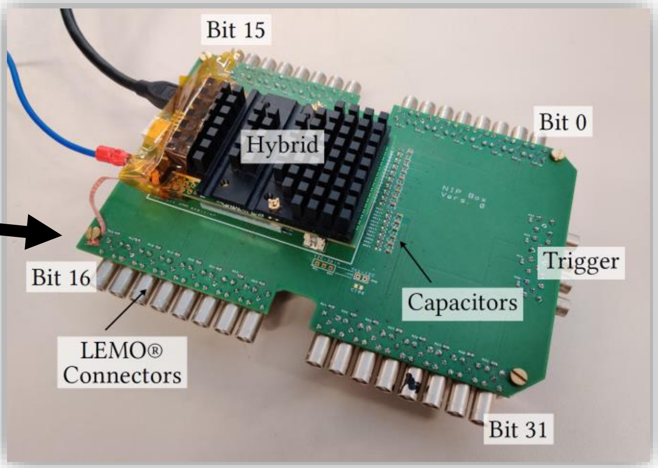


[Courtesy of Marek Gazdzicki]

Self-triggered + externally triggered

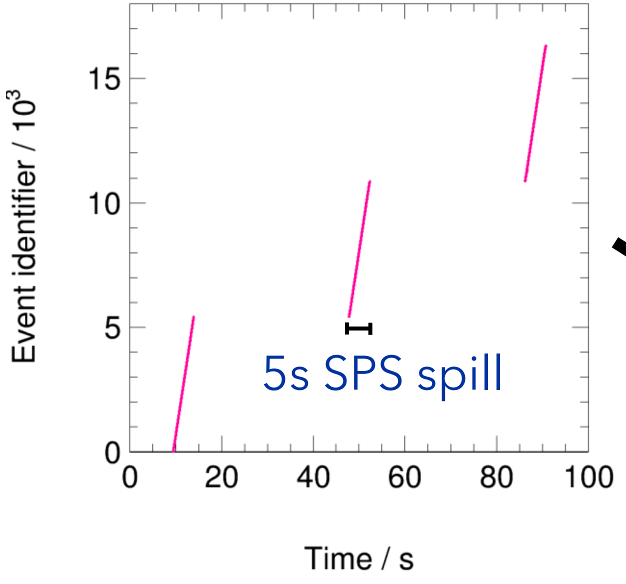
- Ad-hoc interim solution for beam tracking in front of interaction target
- **Five weeks non-stop operation without failure of detectors or electronics!**
- 31 GeV/c protons @ ~ 10 kHz beam rate
- **Challenge:**
  - Beam telescope: self-triggered
  - NA61: externally triggered @ ~ 1 kHz
    → matching NA61 events with VMM3a/SRS tracks
- **Solution:** inject event-ID from NA61 trigger into the VMM3a/SRS data stream
- Split event-ID-bits on VMM readout channels
- Match tracks and events in the offline analysis



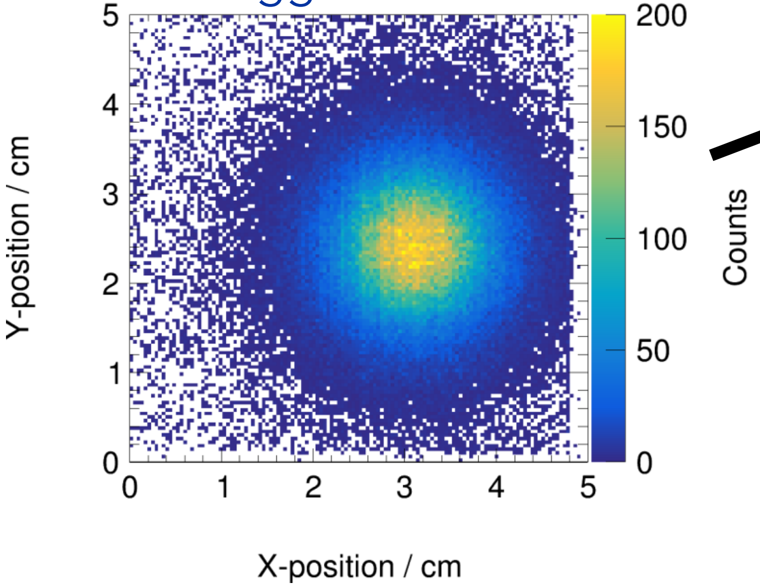


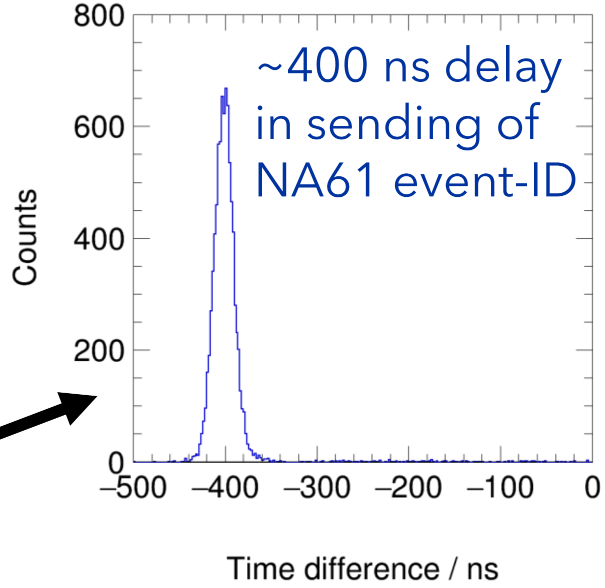
Event matching:
Time

Decoded event-ID

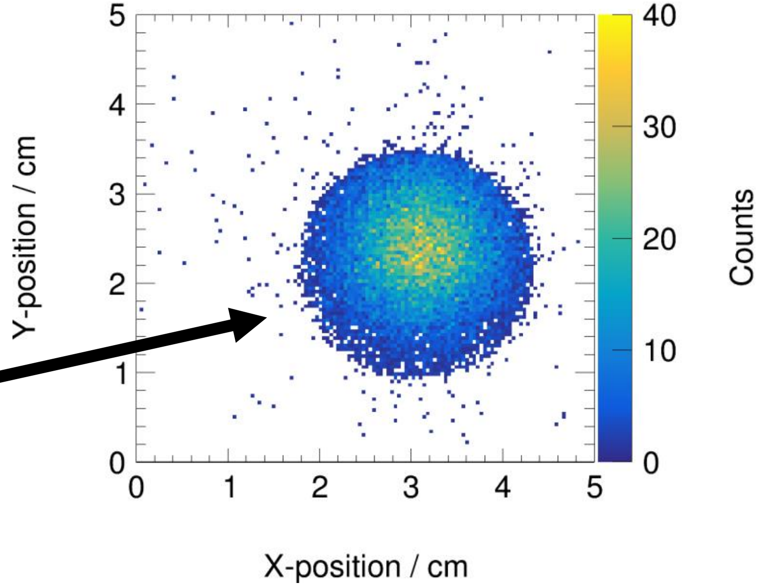


Self-triggered readout





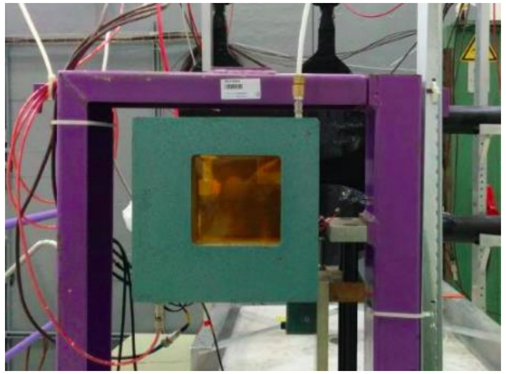
Match event-ID and interactions in tracking detectors in time



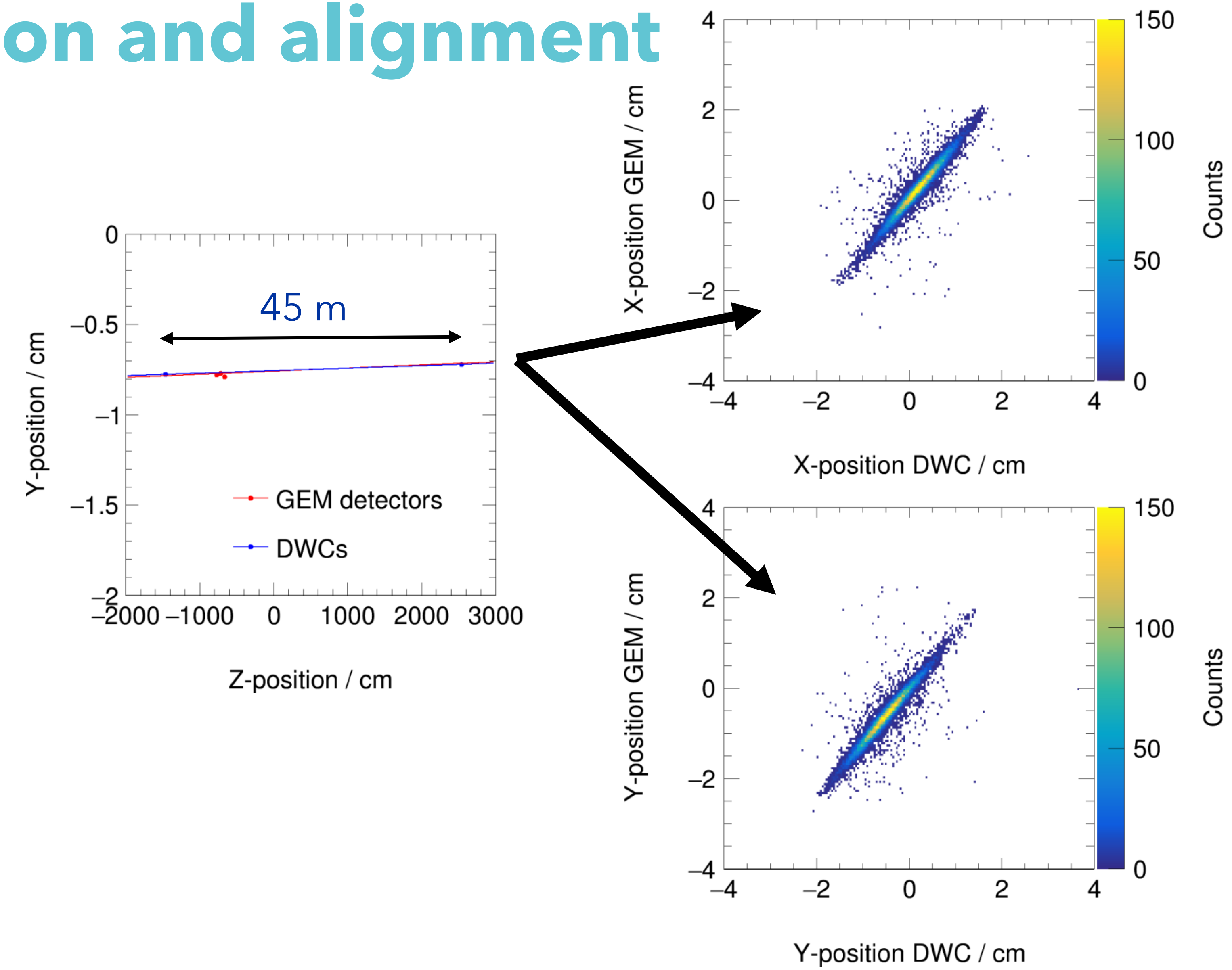
Positions of matched interactions (compatible with scintillators from NA61 trigger-logic)

Event matching:
Position and alignment

- Positions needed in NA61/SHINE coordinate system
- **Alignment run with external reference**
- No target + **Delay Wire Chambers** (DWC) of beam instrumentation



[Courtesy of Brant Rumberger]



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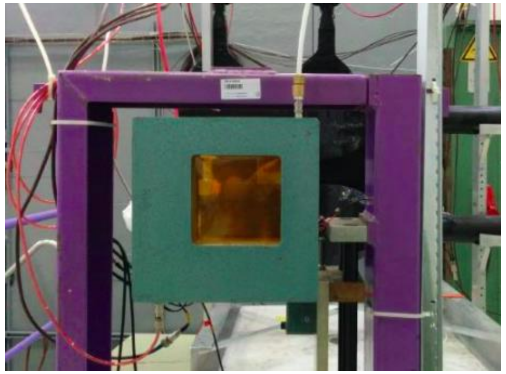
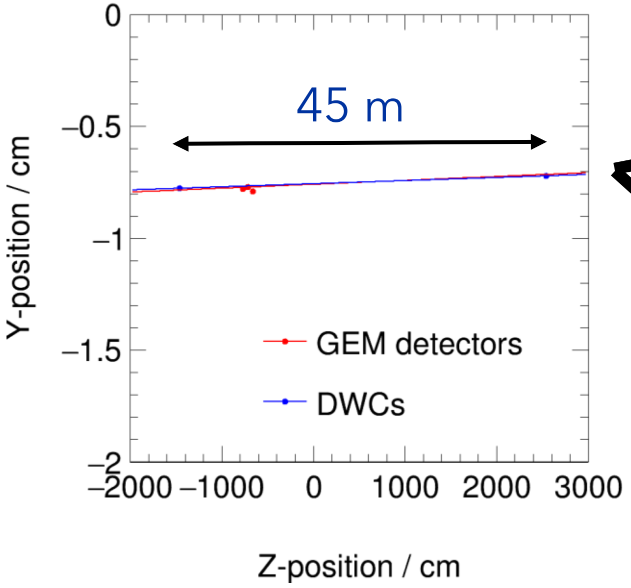
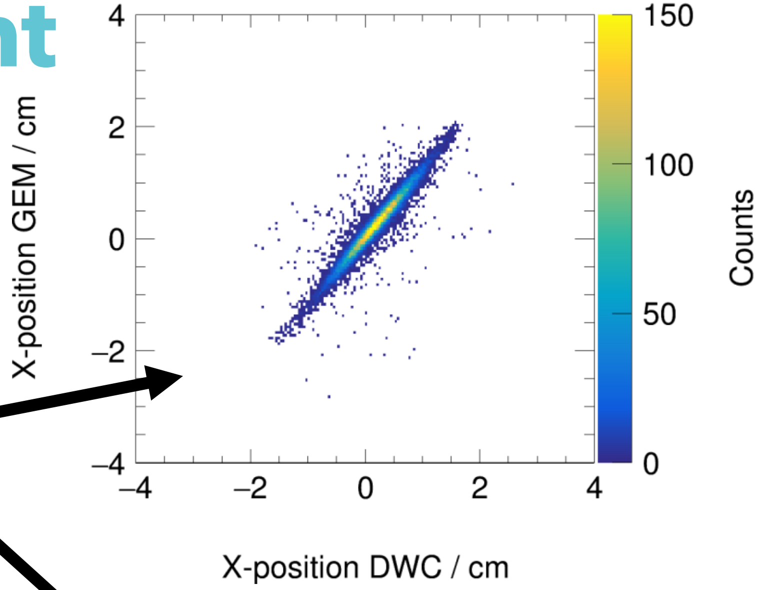
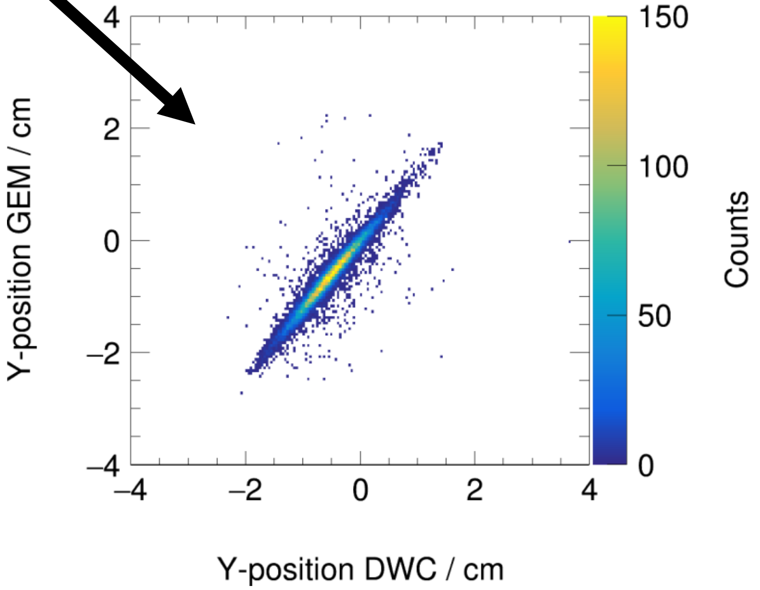


[Courtesy of Brant Rumberger]



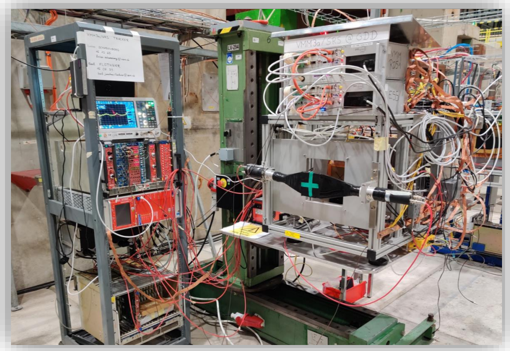




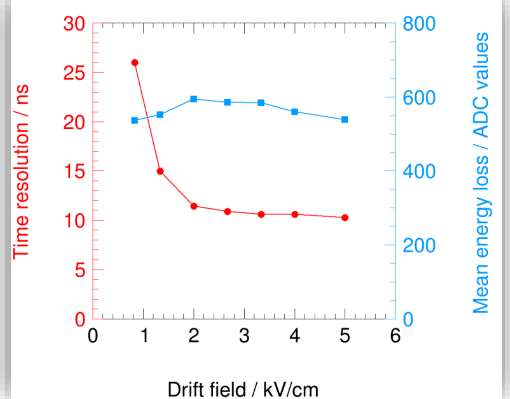
Successful integration of RD51 VMM3a/SRS beam telescope into NA61/SHINE

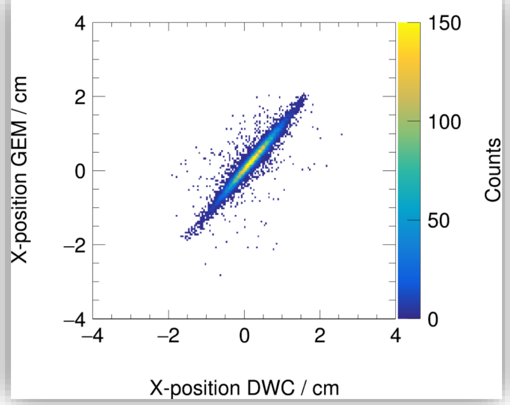
Data used for physics analysis

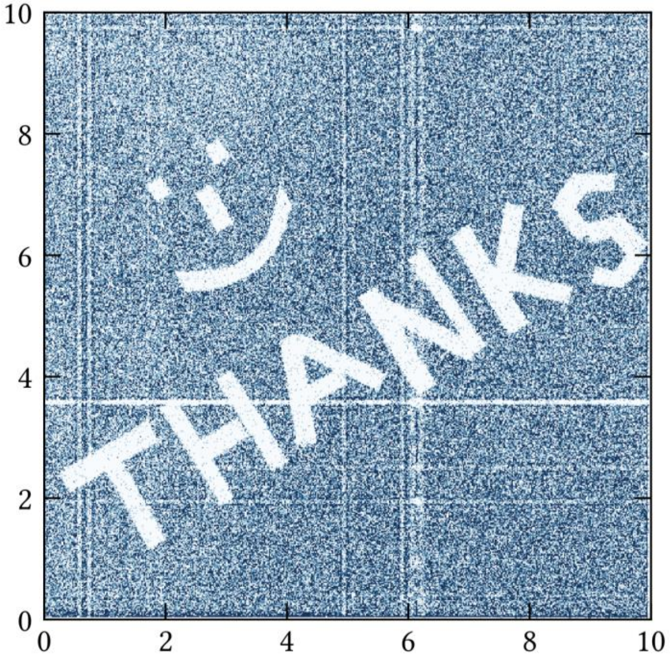
Conclusion



- Commissioned **new beam telescope for RD51** test beam campaigns
- **Time** resolution, **position** resolution, **energy** behaviour can be studied **simultaneously**
- **Particle beams with up to 1 MHz** interaction rate can be recorded
- Various detector technologies (not limited to MPGDs) can be read out
- **Successfully operated as part of the NA61/SHINE** experiment







for your attention!

SPONSORED BY THE
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EP R&D

The work has been supported by the CERN Strategic Programme on Technologies for Future Experiments. https://ep-rnd.web.cern.ch/

SHINE

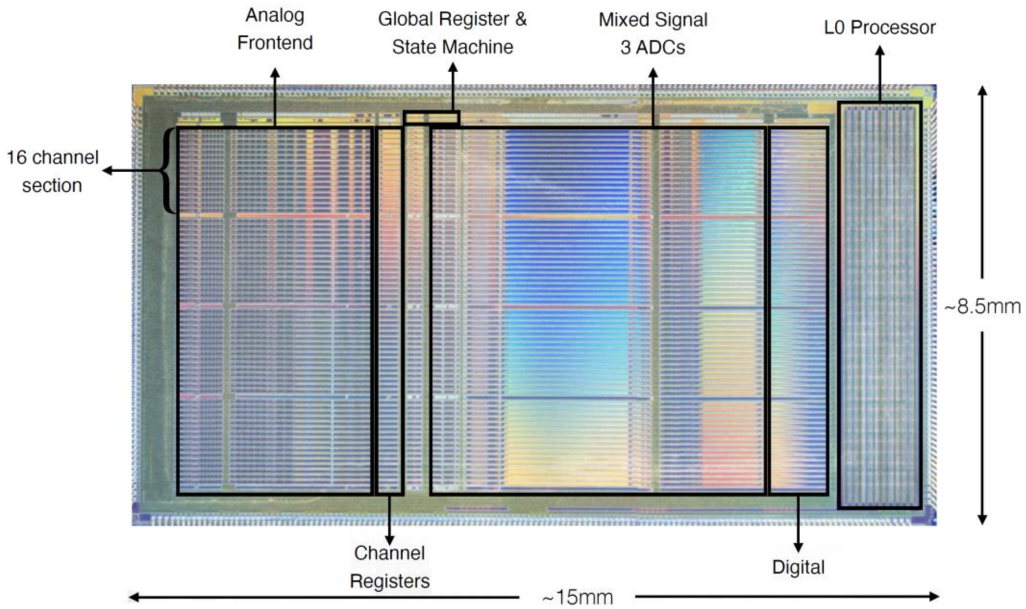
The authors would like to thank all the members of the NA61/SHINE Collaboration for their help and support.

Back-up slides

[1] IEEE TNS **69** (2022) 976-985

ATLAS/BNL VMM3a front-end ASIC

- 64 readout channels
- **Self-triggered continuous readout in SRS implementation**
- 4 Mhits/s per channel, but max. **9 Mhits/s per VMM in SRS implementation**
- Integrated zero-suppression
- 10-bit **charge ADC**
- 12+8-bit **timing with O(ns) time resolution**
- **Adjustable peaking times** (25, 50, 100, 200 ns)
- **Adjustable electronics gains** (0.5, 1.0, 3.0, 4.5, 6.0, 9.0, 12.0, 16.0 mV/fC)
- Neighbouring-logic
- Subhysteresis discrimination
- **Input capacitances (< 200 pF up to 2 nF)**
- …



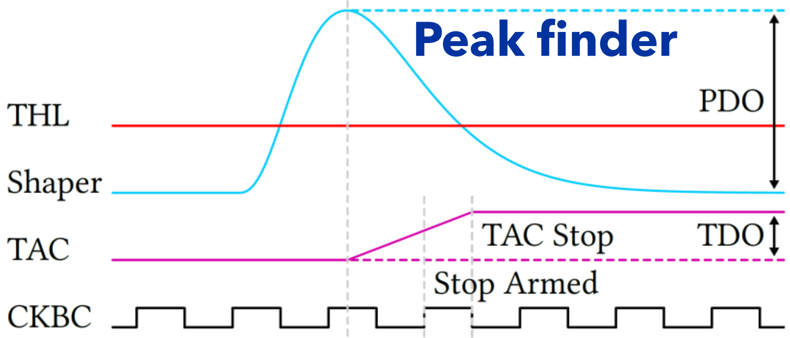
https://indico.cern.ch/event/1040996/contributions/4402617/

Configurability, i.e. peaking times and electronic gain, good for the SRS
→ **Cope with different detector technologies at once**

[1] NIM A **1031** (2022) 166548
[2] IEEE TNS **69** (2022) 976-985

VMM3a front-end of the SRS

Each VMM channel signal = 40-bit in SRS implementation



Clockless ADC (10-bit), **only peak amplitude**

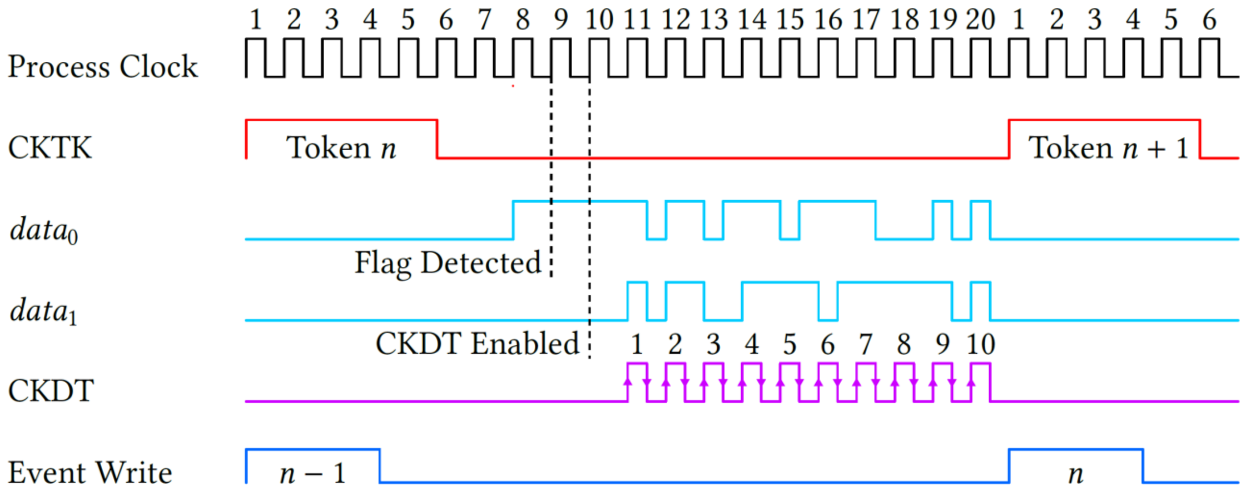
Over-threshold flag (1-bit)

TDC (8-bit **fine timestamp**)

Reference clock (12-bit **coarse counter**)

+ data-flag (1-bit)
+ channel number (6-bit)
+ extra bits for 8b/10b
+ encoding (2-bit)

Token passing scheme to read the data from the channel for continuous readout

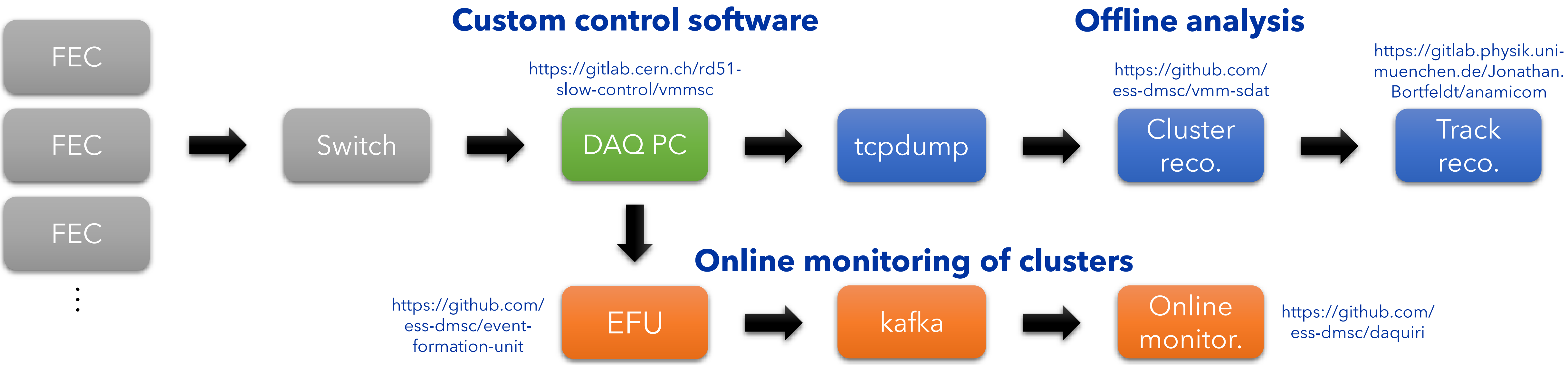


1. Token is sent
2. Data flag is detected
3. Data transmission is started
4. Event is written to buffer for 8b/10b encoding
5. Data are sent via SERDES on LVDS lines to adapter card

Maximally 9 Mhits/s per VMM

[1] NIM A **1031** (2022) 166548
[2] https://vmm-srs.docs.cern.ch/
[3] Control software

Data processing software



Custom control software

https://gitlab.cern.ch/rd51-slow-control/vmmsc

Offline analysis

https://github.com/ess-dmsc/vmm-sdat

https://gitlab.physik.uni-muenchen.de/Jonathan.Bortfeldt/anamicom

FEC

FEC

FEC

⋮

Switch

DAQ PC

tcpdump

Cluster reco.

Track reco.

Online monitoring of clusters

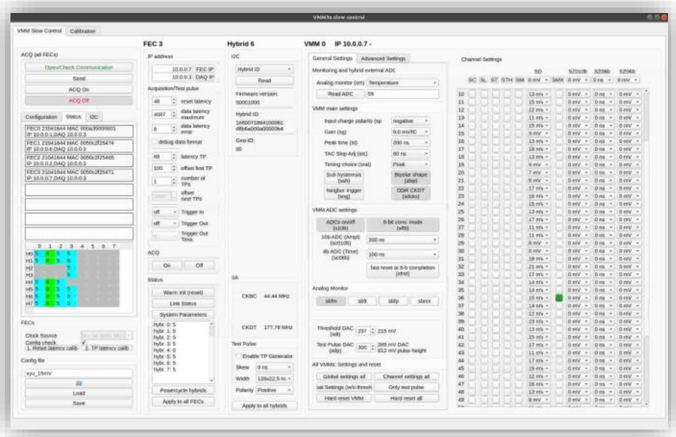
https://github.com/ess-dmsc/event-formation-unit

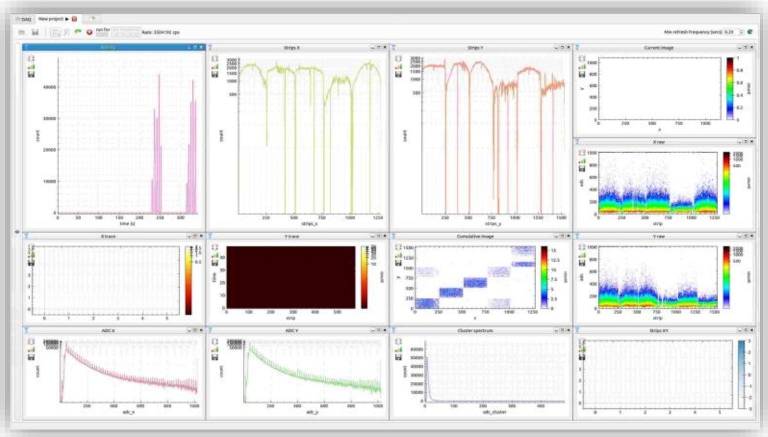
EFU

kafka

Online monitor.

https://github.com/ess-dmsc/daquiri

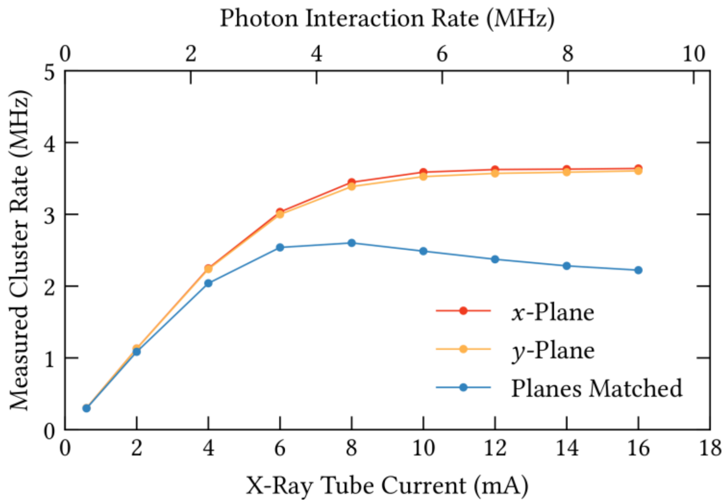




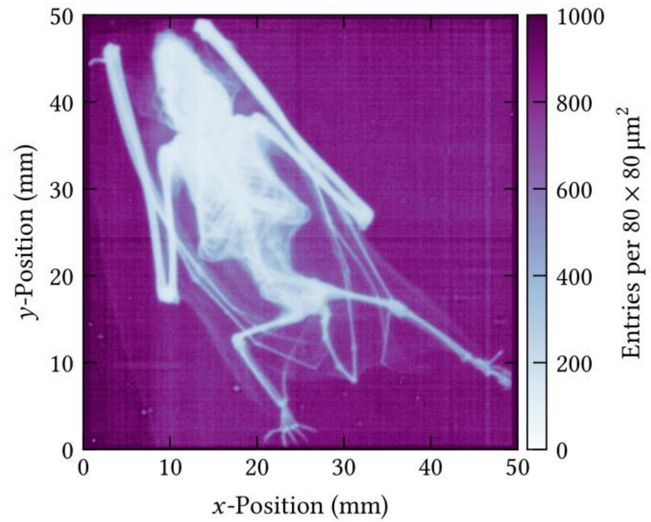
[1] NIM A **1031** (2022) 166548

High-rate measurements (X-ray)

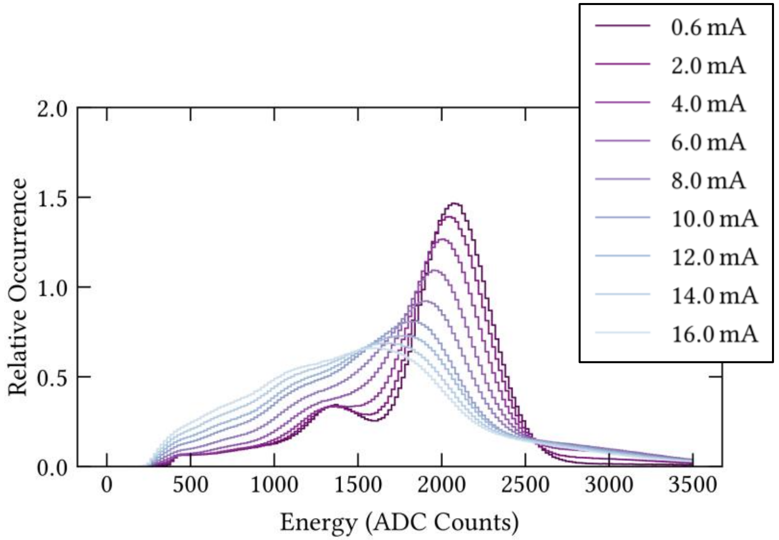
- Measurements with copper target X-ray tube
- Rate-optimised setup: 1 hybrid per FEC (18 Mhits/s per hybrid), 2 FECs
- COMPASS-like triple-GEM detector, 256+256 x-y-strip readout (400 µm pitch)



Saturation of recorded interaction rate
Cluster contains ~5 strips per plane



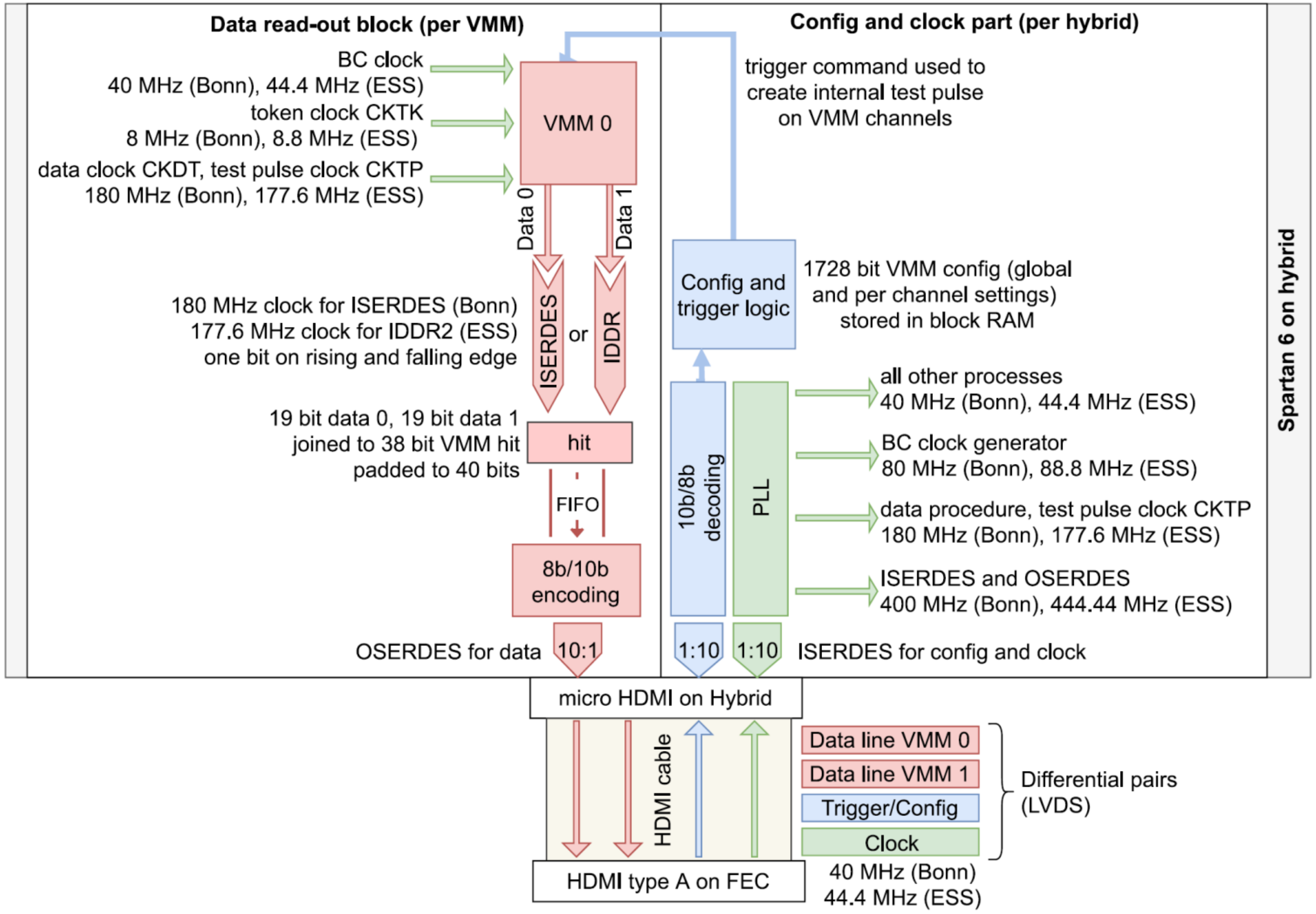
High-rate X-ray imaging
(280 x 10^6 recorded photons in 3 minutes)
Access to energy, position and time of photon



Degradation of spectrum, due to missing cluster information

[1] NIM A **1031** (2022) 166548

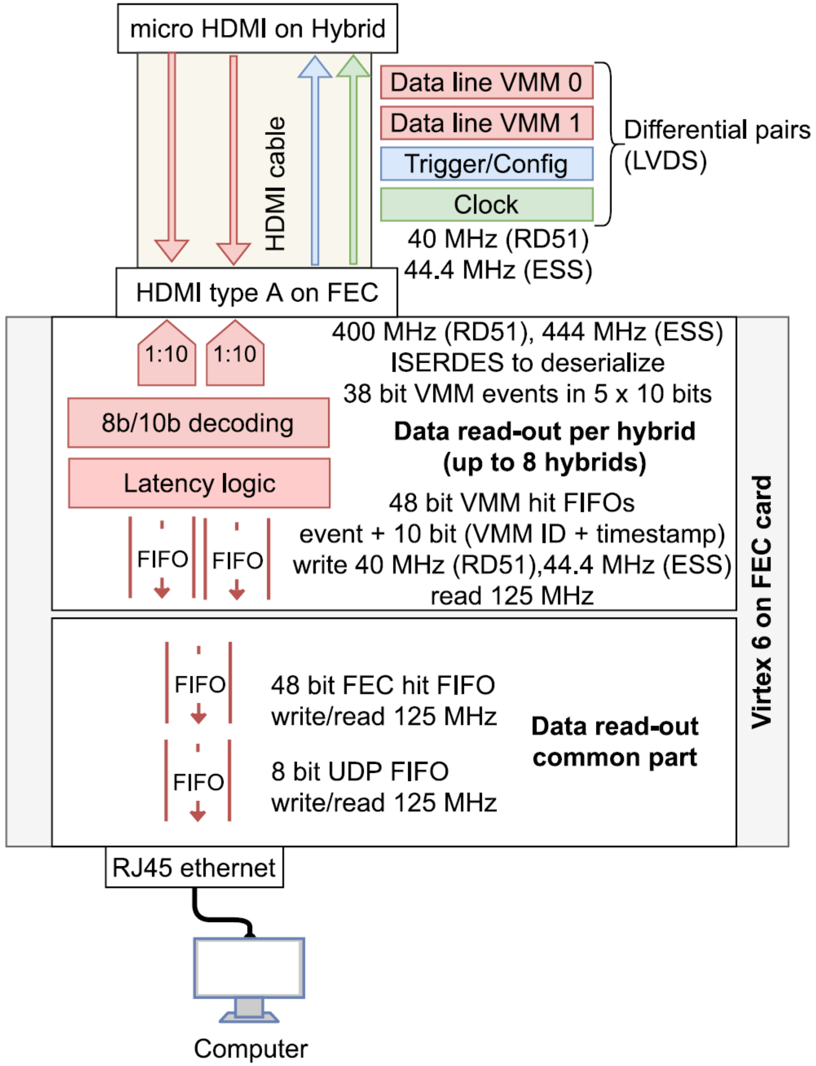
VMM3a/SRS firmware (hybrid)



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

[1] NIM A **1031** (2022) 166548

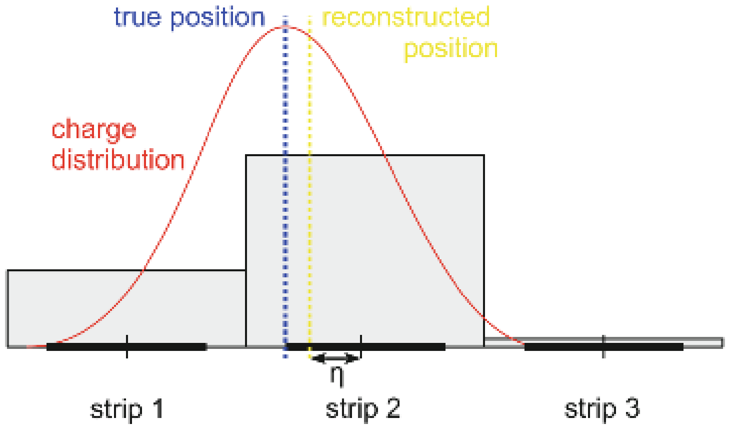
VMM3a/SRS firmware (FEC)



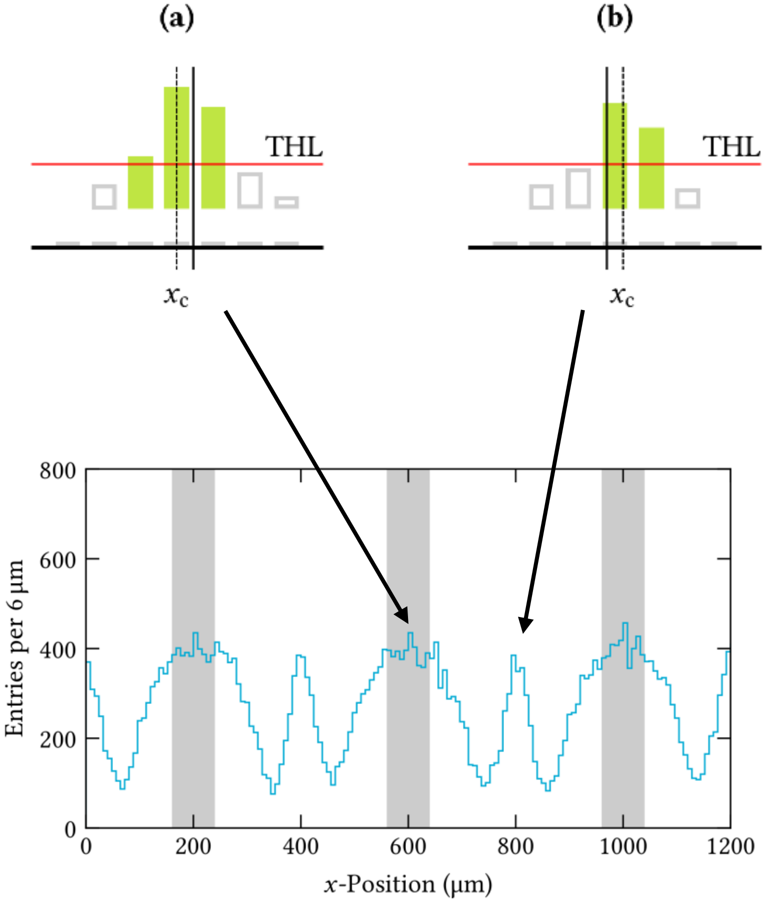
https://doi.org/10.1016/j.nima.2022.166548

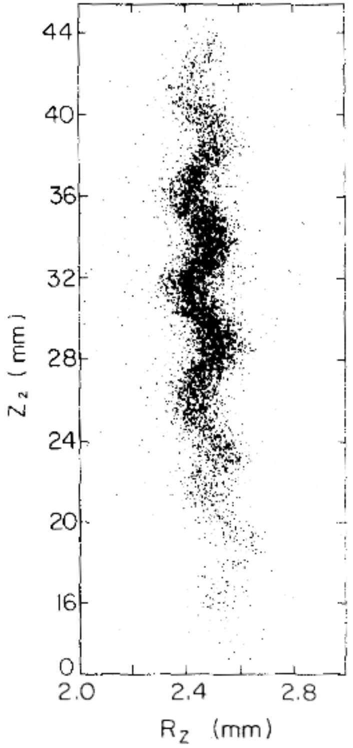
[1] NIM A **1011** (2021) 165576

Modulation of readout pattern



https://doi.org/10.1007/978-3-319-18893-5



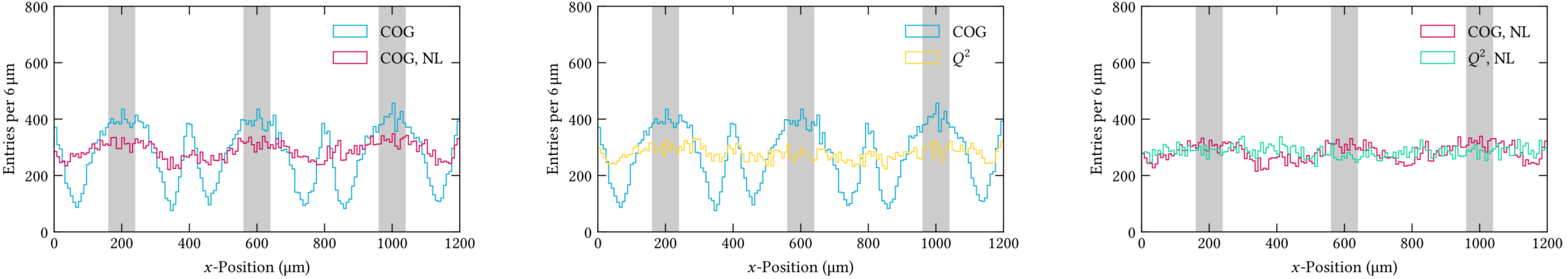


NIM **196** (1982) 451-462

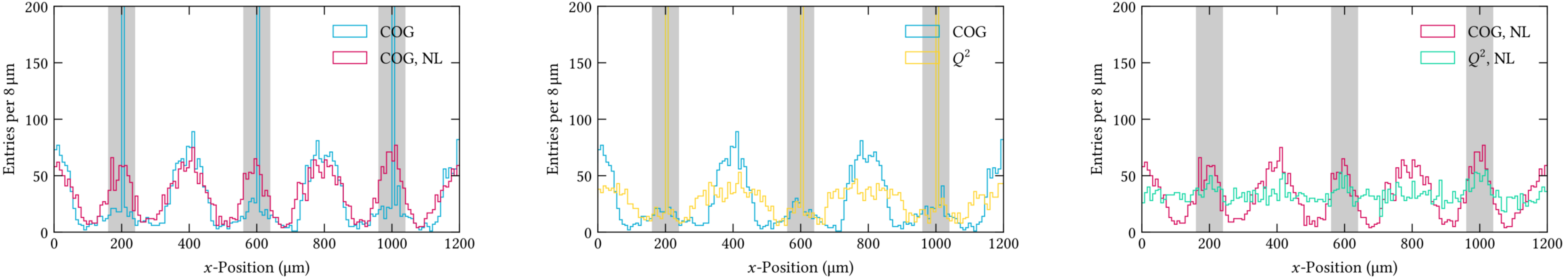
[1] NIM A **1011** (2021) 165576

Modulation of readout pattern

X-rays



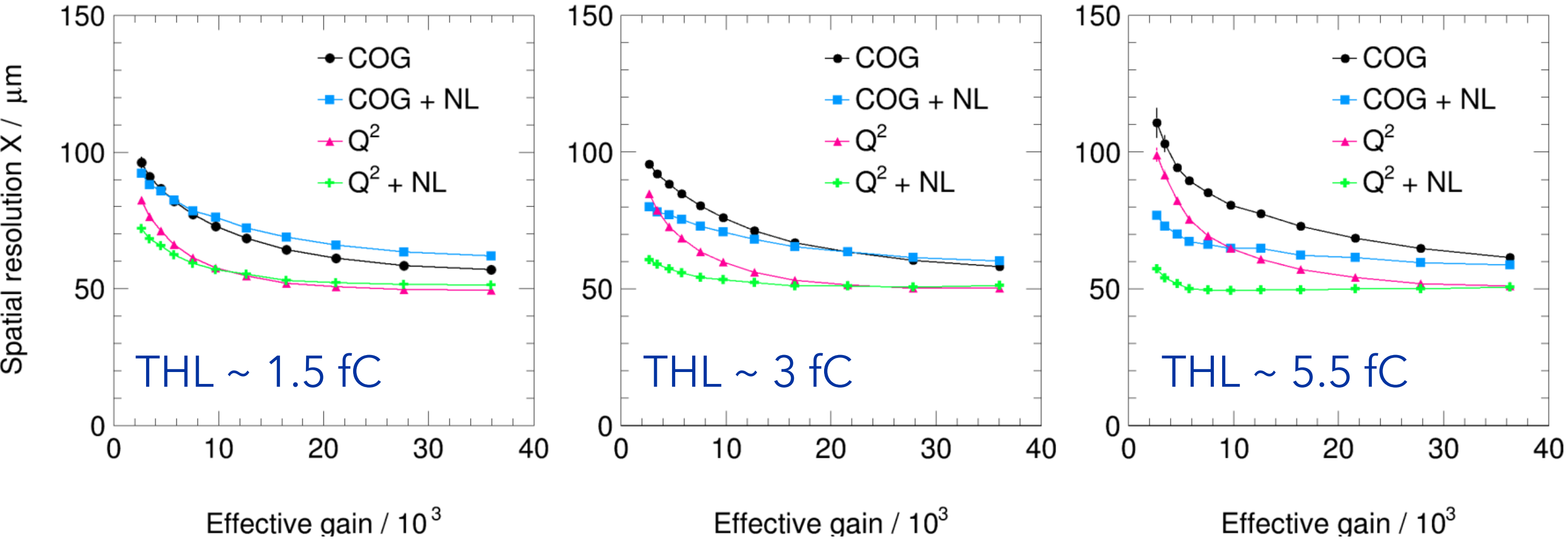
MIPs



[1] NIM A **1011** (2021) 165576

Improving spatial resolution

Triple-GEM detector (256+256 x-y-strips, 400 µm pitch)



µRWELL (256+256 x-y-strips, 400 µm pitch)