Evolution and applications of the RD51 VMM3a/SRS gaseous beam telescope

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

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CERN UNIVERSITÄT BONN SPONSORED BY THE Federal Ministry of Education and Research EP R&D AIDA innova ess EUROPEAN SPALLATION SOURCE RD51 Collaboration GDD Gas Detectors Development Group CERN

Outline

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   - RD51 Scalable Readout System (SRS)

2. **Telescope's performance**
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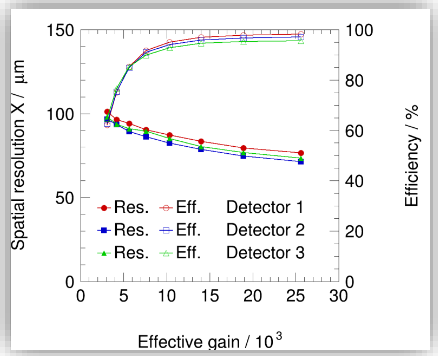
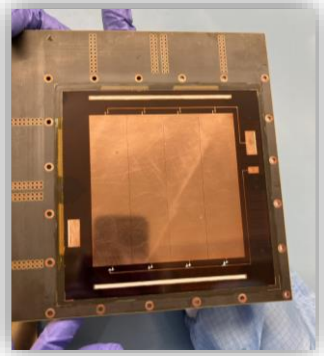
   - Rate-capability

3. **Detectors under test**
   - Micro-resistive WELL (µRWELL)

4. **Operation at NA61/SHINE**
   - Combining self-triggered and externally triggered readout
   - Offline event-matching



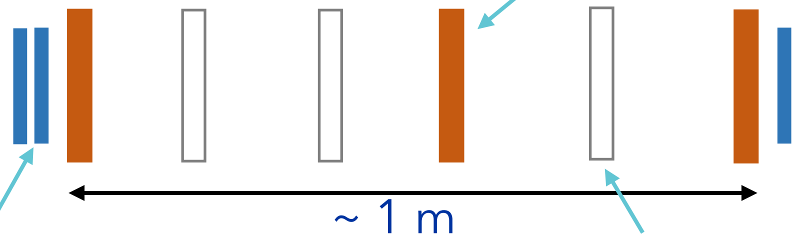


Test beam campaigns of RD51

- **RD51**: CERN-based R&D collaboration on the development of **Micro-Pattern Gaseous Detectors** (MPGDs)
- Test beam campaigns for detector tests: **H4 beam line @ CERN's SPS (PPE 134)**
- Infrastructure contains (amongst other things) **two beam telescopes**
  - → Gas Electron Multiplier (GEM)-based
  - → MicroMegas-based
  - → **Strip** or **pad readout anode**
  - → Read out with RD51 Scalable Readout System (SRS)

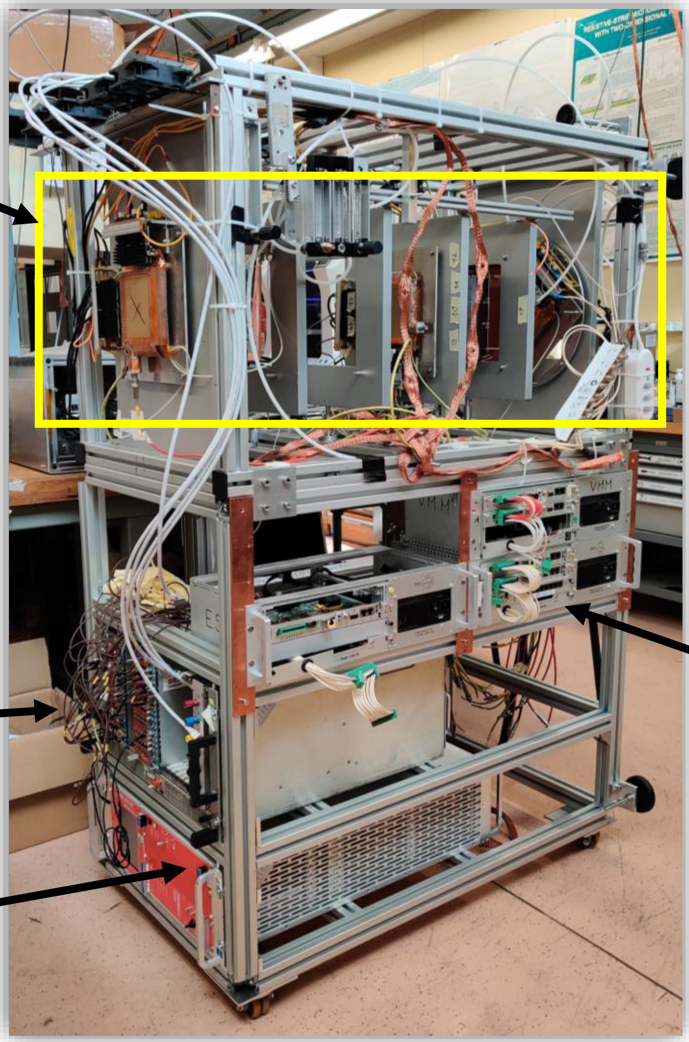
Test beam campaigns of RD51:
Triple-GEM telescope

3 reference tracking detectors
→ x-y-strips (256 + 256)



Scintillators for timing

DUTs



COMPASS-like triple-GEM detectors [1] for tracking
→ filled with Ar/CO_2 (70/30 %)
→ strips with 400 μm pitch

10 x 10 cm² active area (facing the beam)

NIM-logic for scintillator/PMTs
(read out via VMM3a in the RD51 SRS)

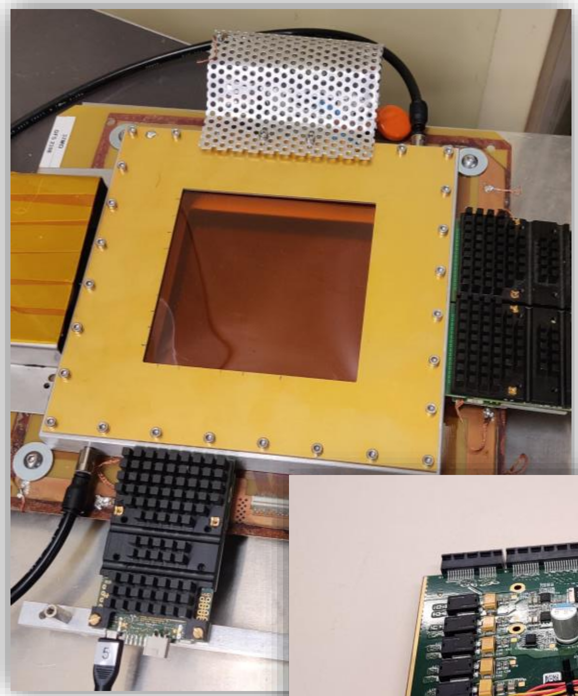
RD51 SRS electronics with VMM3a front-end ASIC [2]
More than 2k channels for DUTs

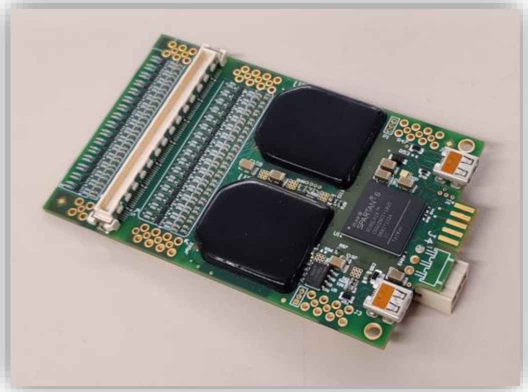
High voltage for detectors

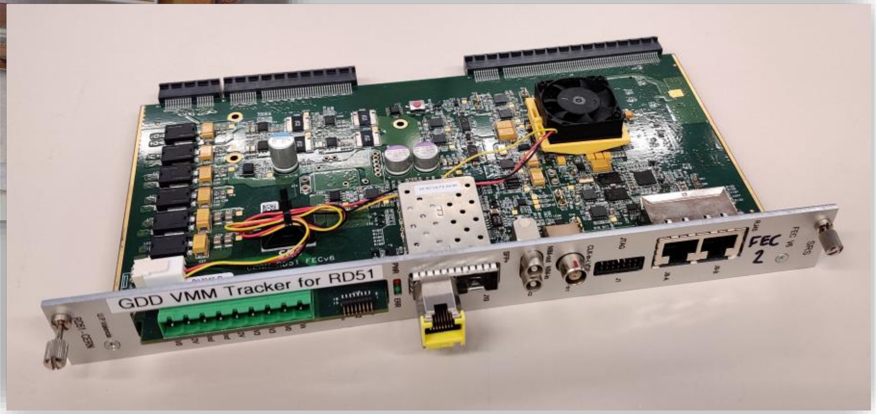
[1] NIM A **490** (2002) 177
[2] JINST **17** (2022) C12014

Readout electronics:
RD51 Scalable Readout System (SRS)

- Common RD51 readout system for **small R&D setups up to mid-sized experiments** [1,2]
  → Ideal for readout of beam telescope with multiple detectors
- Front-end ASICs available for beam telescopes
  → Since 2009: **APV25**
  → Since 2021: **VMM3a**





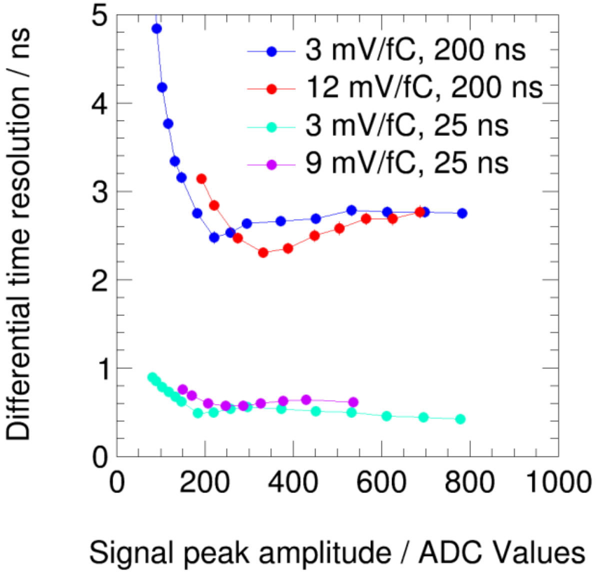


- Front-end ASIC plugged onto the detector via **hybrid-PCB**
- ASIC-specific adapter card with multiple hybrids
- Common Front-End Concentrator (**FEC**)
- Multiple FEC/adapter cards for larger systems

[1] JINST **8** (2013) C03015
[2] NIM A **1031** (2022) 166548

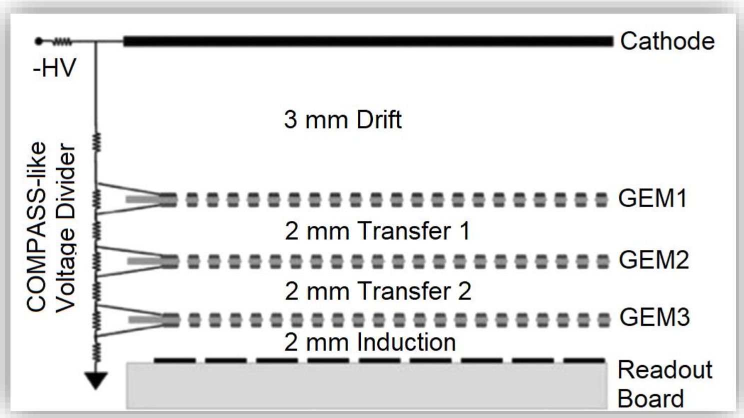
Readout electronics:
ATLAS/BNL VMM3a front-end ASIC

- Specifically developed by BNL for multi-channel readout of gaseous detectors (ATLAS New Small Wheel) [1]
- **Self-triggered continuous readout** in SRS implementation
- High rate capability: **9 Mhits/s per VMM** in SRS implementation
- Provides only **peak amplitude** (10-bit charge ADC)
- Provides **time of the peak** with O(ns) time resolution (12+8-bit timing)
- Good for R & D applications
  - Adjustable peaking times
  - Adjustable electronics gains
  - Wide range of input capacitances (< 200 pF up to 2 nF)
- **Full detector characterisation with charge, space and time information with same front-end electronics**

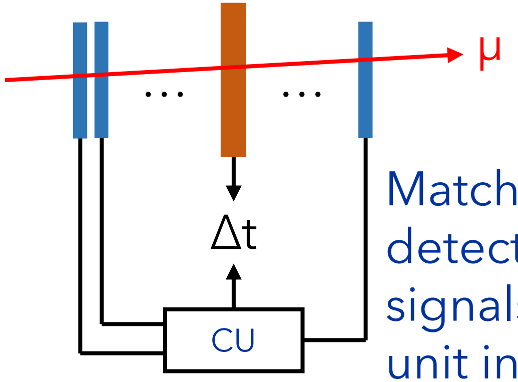


[1] IEEE TNS **69** (2022) 976

Beam telescope's performance:
Detector-based studies

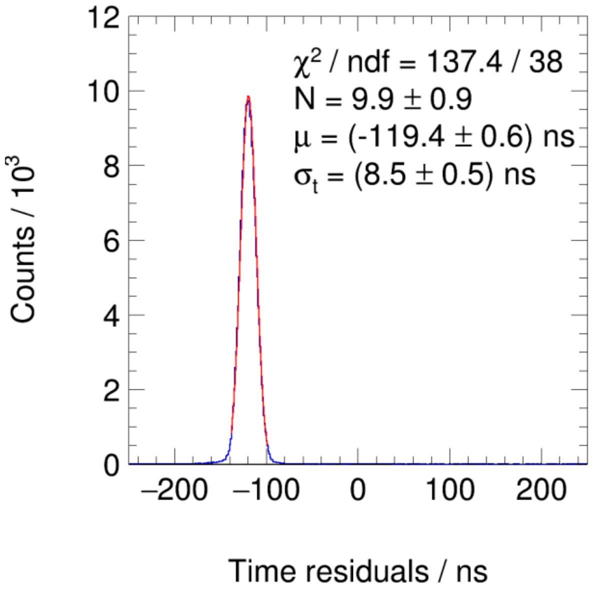


NIM A **805** (2016) 2-24

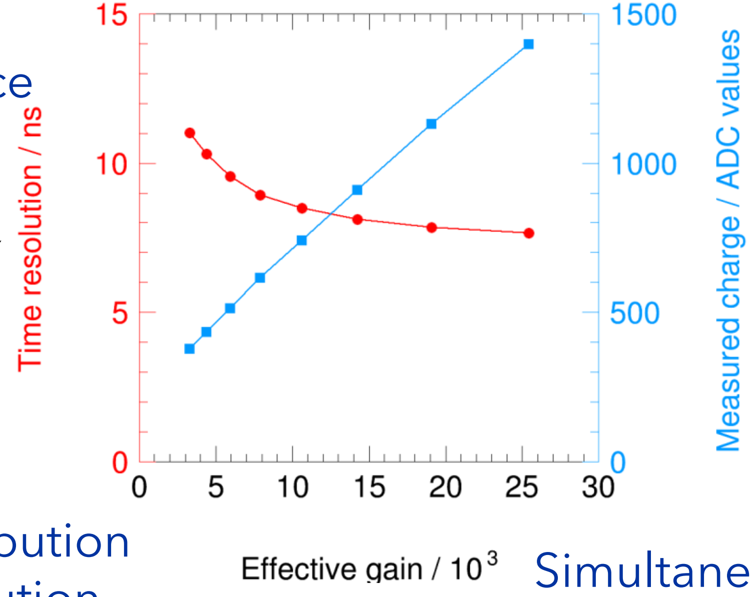


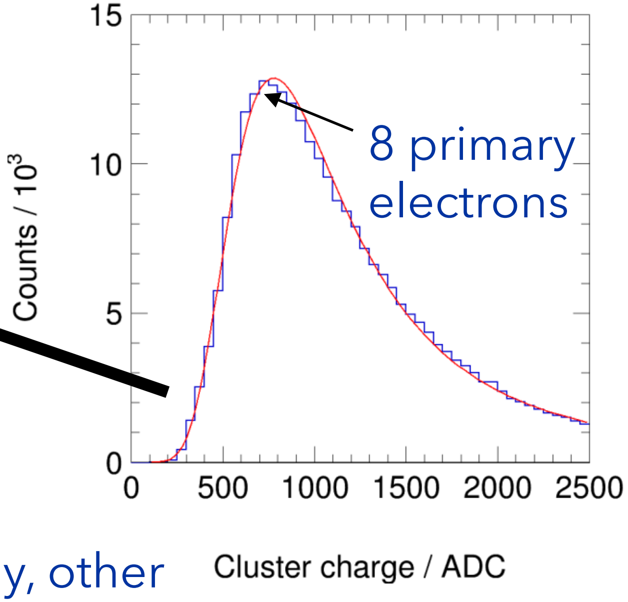
Event building based on signal arrival time, using *vmm-sdat* [1]

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



Width of time difference distribution gives time resolution



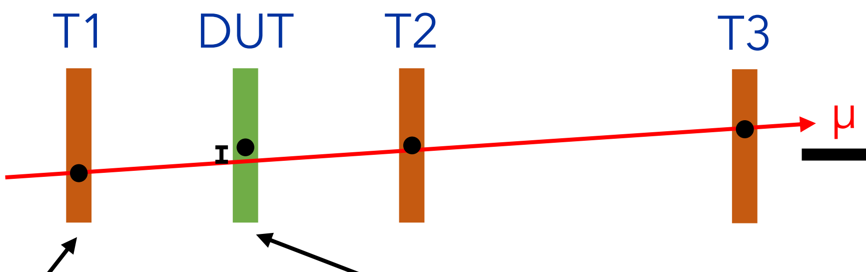


Simultaneously, other information from clusters with matching time provided

[1] vmm-sdat

Beam telescope's performance: Track-based studies

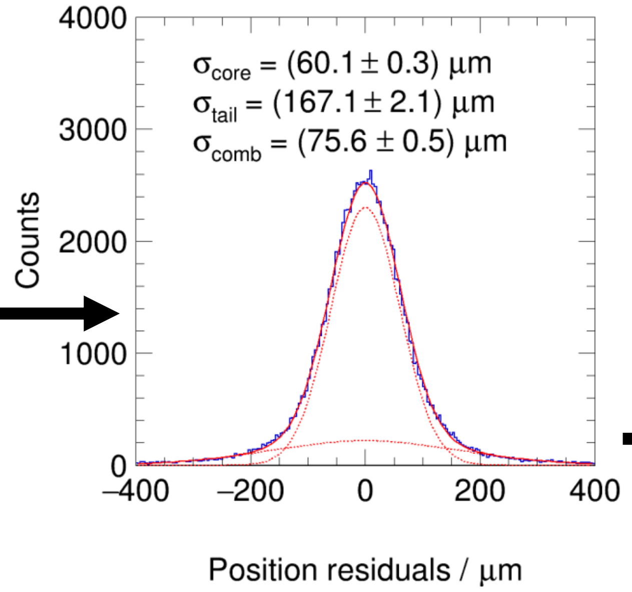
- Position determination: **Centre-of-gravity (COG)**, as well as **alternative approaches** [1,2]
- Event-building based on cluster time
- Tracking with **Kalman filter** via *anamicom* [3]
- **Spatial resolution studies** as in [4]
- Tracking error as in [5]



$\sigma_{\text{pos}} = \sqrt{\sigma_{\text{in}}\sigma_{\text{ex}}}$ [6]

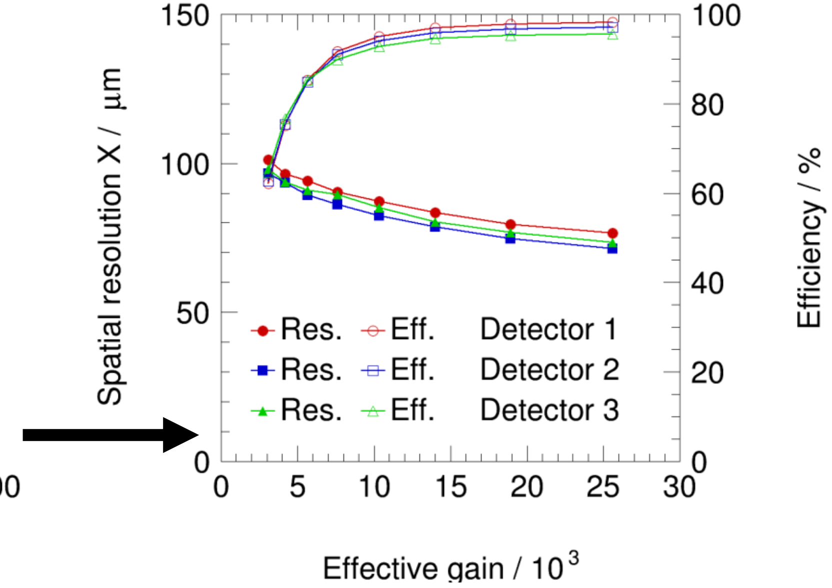
$\sigma_{\text{pos}} = \sqrt{\sigma_{\text{ex}}^2 - \sigma_{\text{track}}^2}$

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



~10 kHz recorded interaction rate

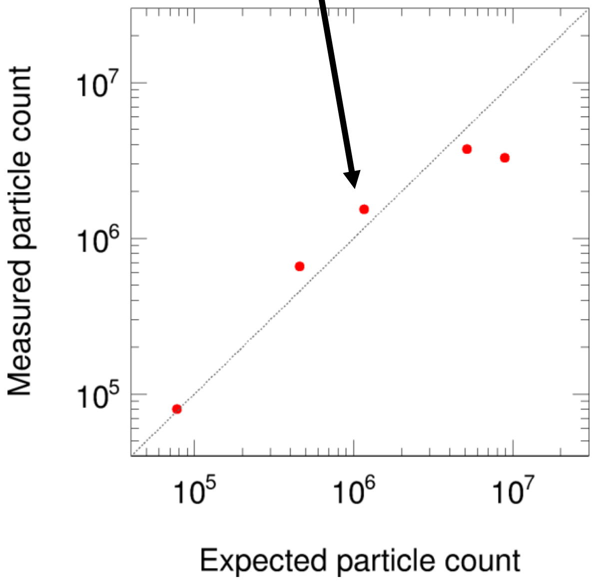
Efficiency not @ 100% due to geometrical effects and non-working readout channels

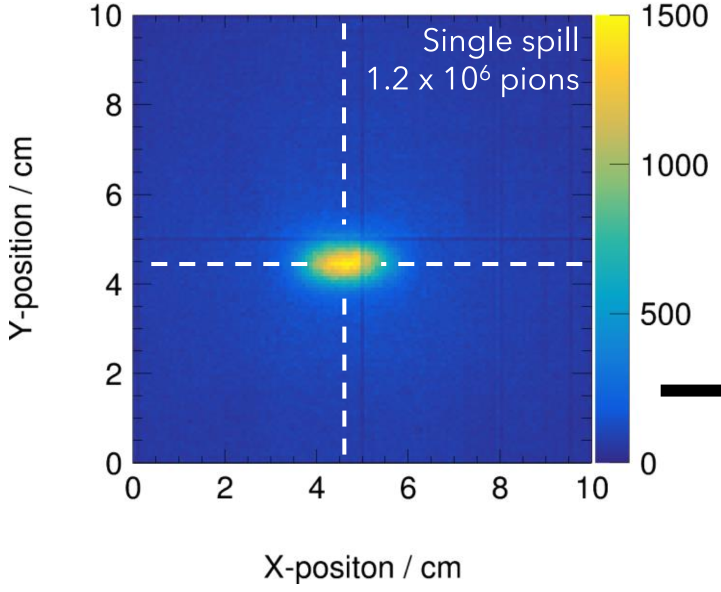


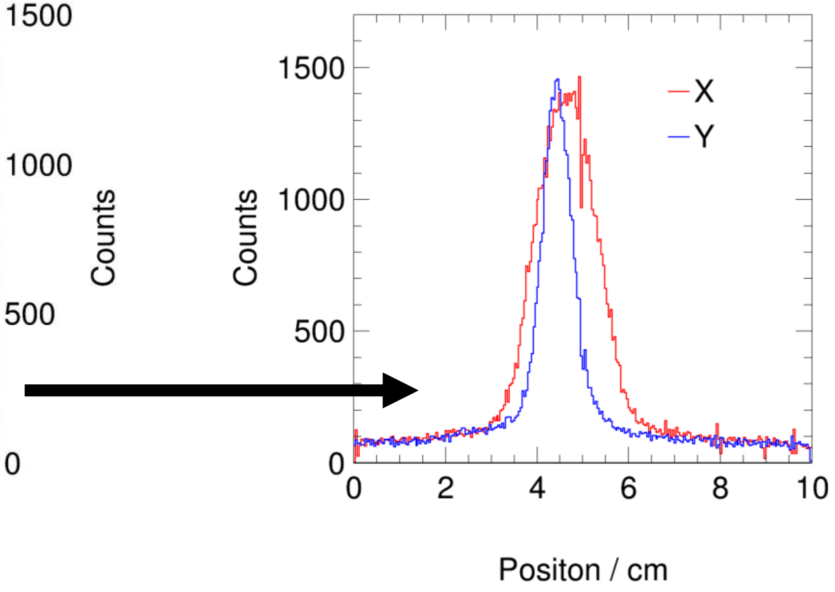
[1] NIM A **1011** (2021) 165576 [2] arXiv: 2302.08330
[3] anamicom [4] J. Bortfeldt (PhD thesis)
[5] S. Horvat (PhD thesis) [6] NIM A **538** (2004) 372-383

Beam telescope's performance:
Rate-capability

~1.5 x 10^6 particles per spill each particle interaction can be recorded







- 80 GeV/c pion beam: particle flux from ~7 x 10^4 particles per spill (~5 s) to 10^7 particles per spill
- **Bandwidth saturation** with ~5 x 10^6 particles per spill and more
- Limiting factors: **SRS FEC's Gigabit Ethernet** and **9 Mhits/s readout limit of VMM3a**
  - → Loss in number of recorded interactions
  - → Decrease of quality of acquired data, as described in [1]

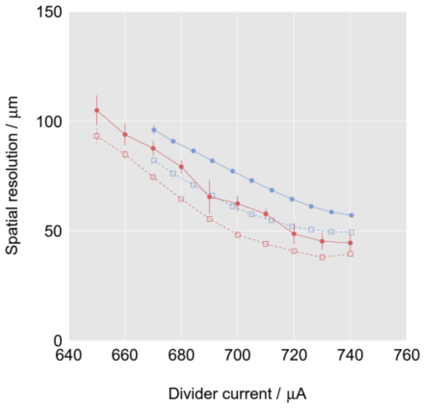
[1] NIM A **1031** (2022) 166548

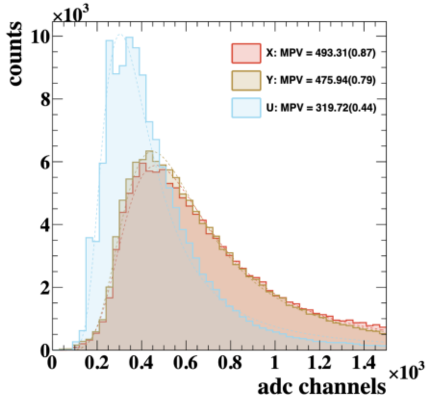
Detectors under test

Triple-GEM

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

Three layer **XYU readout** board [1]
→ ambiguity free readout
→ spatial resol.

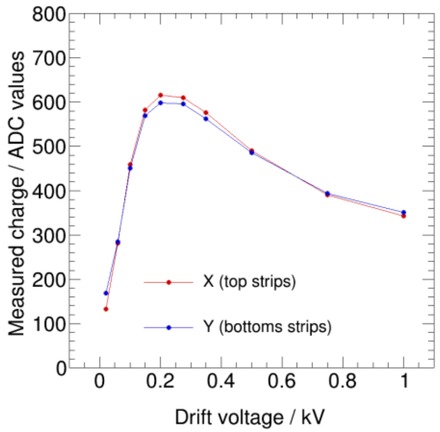




[1] https://arxiv.org/abs/2303.18105

Resistive-plane MicroMegas

Thin-mesh MicroMegas
→ stability
→ higher gain

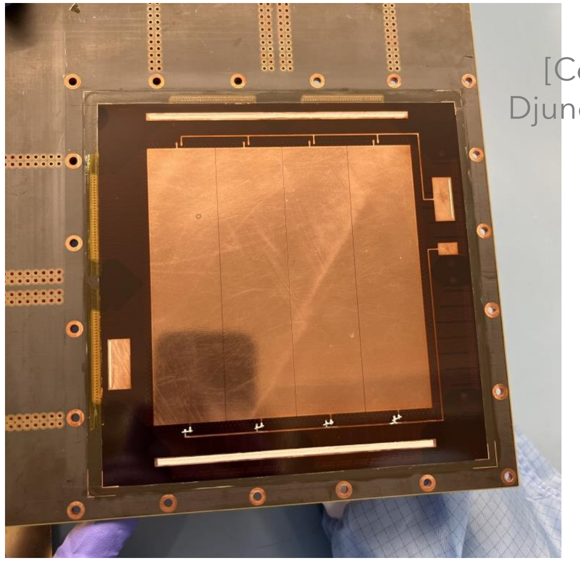


Small-pad MM [2]
→ benchmark XYU readout

[2] https://doi.org/10.1016/j.nima.2022.167944

micro-resistive WELL

μRWELL [3]
→ low material budget
→ planned for use in a third telescope



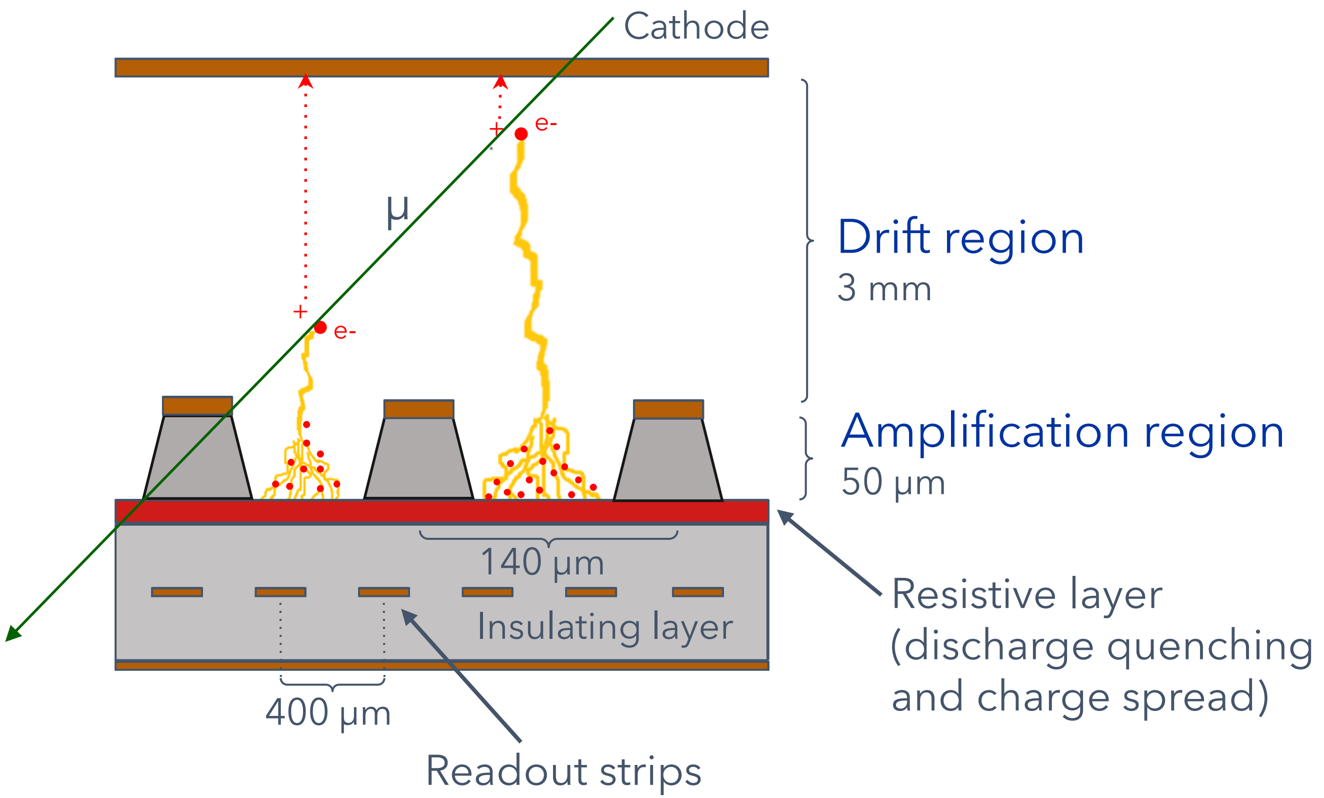
[Courtesy of Djunes Janssens]

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

Studies on the micro-resistive WELL (µRWELL)

- Attractive because of
  - → low material budget
  - → simple manufacturing process
- GEM-foil glued on readout PCB
- **Third RD51 beam telescope to be built, based on µRWELL**

- 10 x 10 cm²
- 256+256 x-y-strips, 400 µm pitch
- 3 mm drift gap
- Filled with Ar/CO_2 (70/30 %)
- Resistive layer with 40 MΩ/□



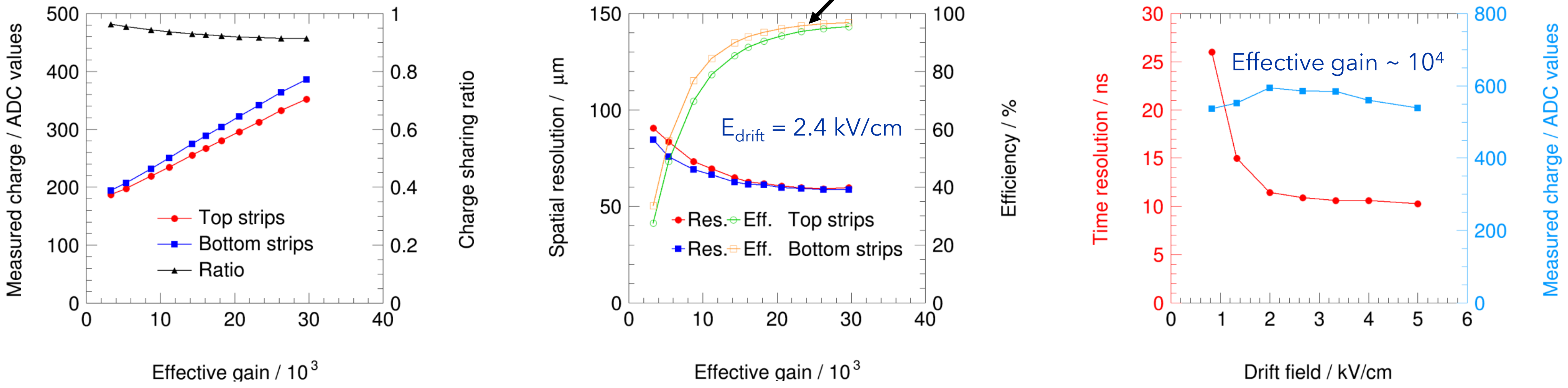
Not drawn to scale

[Courtesy of Djunes Janssens]

Studies on the micro-resistive WELL (µRWELL)

- µRWELL **from Yi Zhou and Xu Wang from USTC** [1]
- **Optimised for equal charge sharing between top and bottom strips (X and Y strips)**
- Not optimised for high-rate operation

High gains needed to reach full efficiency, due to self-triggered readout (higher electronics threshold required)

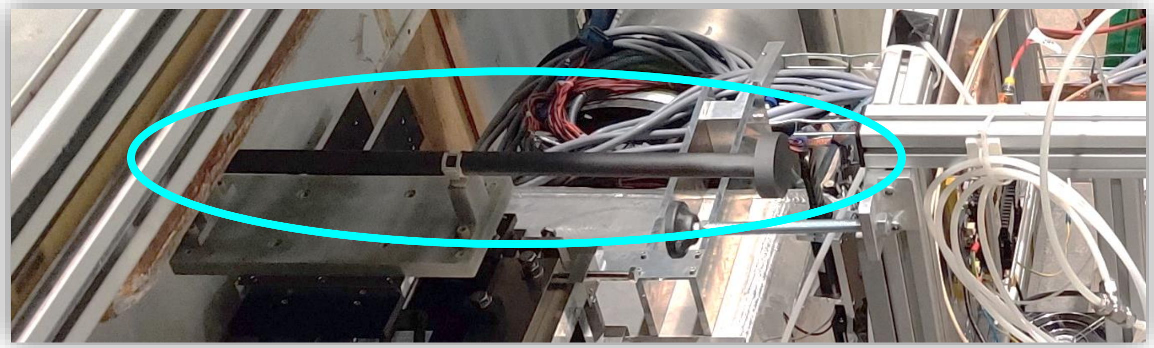


- Simultaneous detector characterisation in energy, space and time

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

The NA61/SHINE experiment

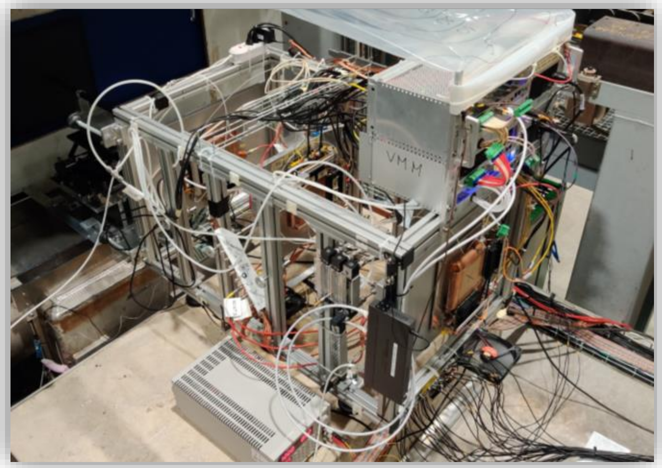
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment (SHINE)
  - Strong interactions (**heavy ion collisions**):
    → Phases of strongly interacting matter
    → **Onset of deconfinement**
  - Interactions of cosmic rays in the interstellar medium (**light ion collisions**): Pierre Auger Observatory, **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

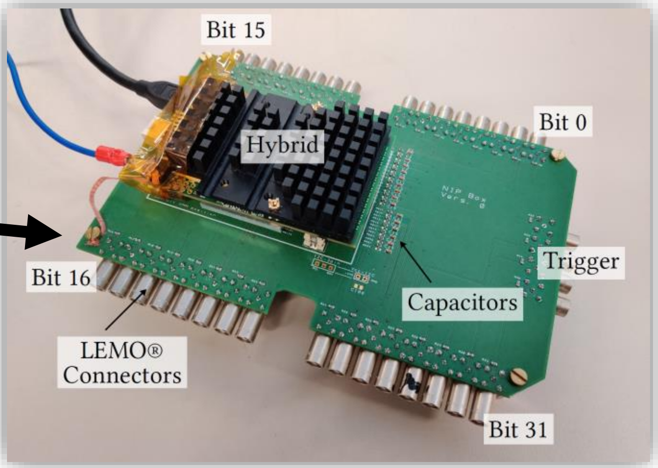


[Courtesy of Marek Gazdzicki]

Self-triggered + externally triggered

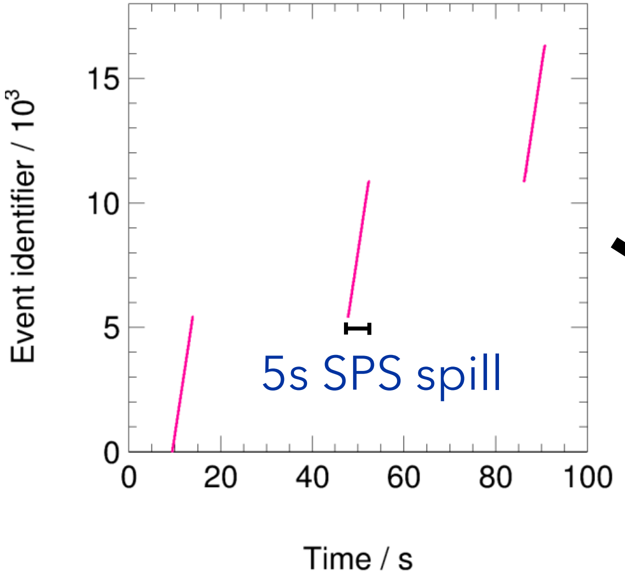
- Ad-hoc interim solution for beam tracking in front of interaction target
- **Five weeks non-stop operation without failure of detectors or VMM3a/SRS electronics!**
- 31 GeV/c protons @ up to 50 x 10^3 particles per SPS spill
- **Challenge:**
  - Beam telescope: self-triggered
  - NA61: externally triggered @ ~ 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



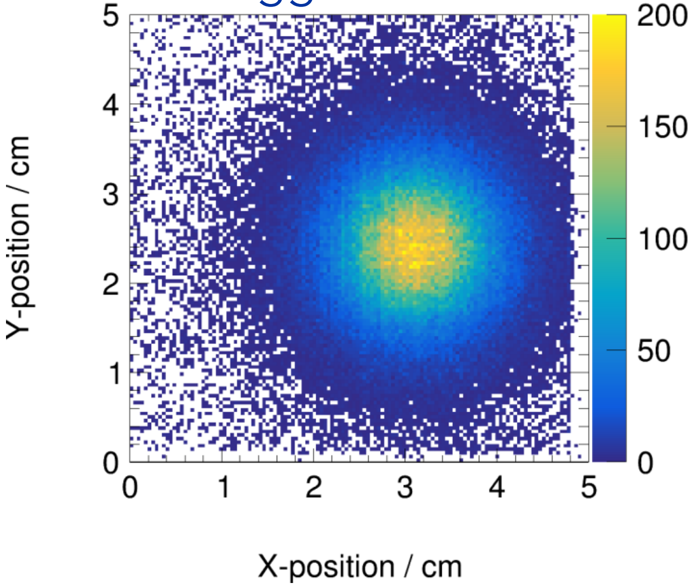


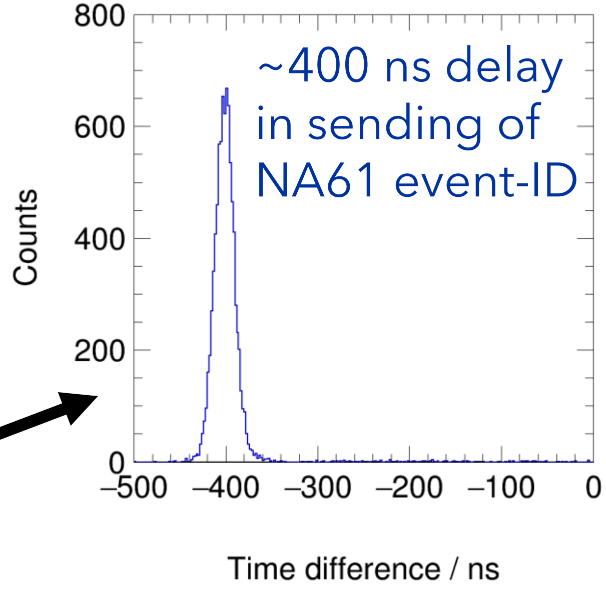
Event matching: Time

Decoded event-ID

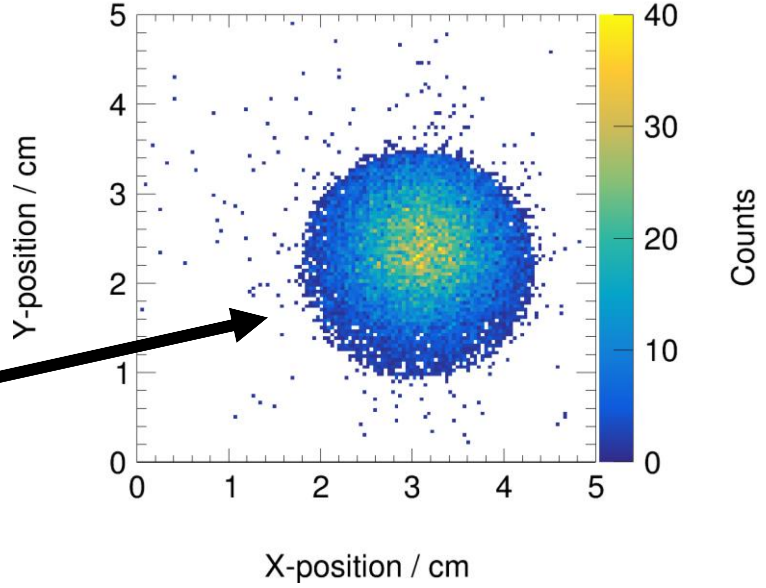


Self-triggered readout





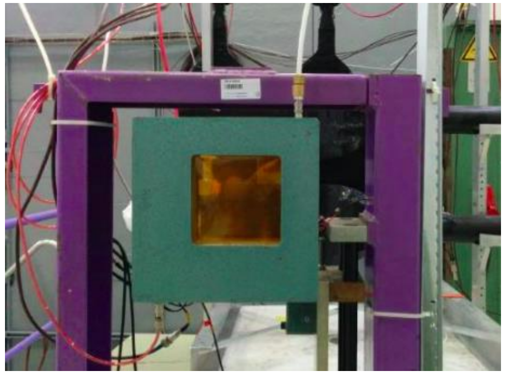
Match event-ID and interactions in tracking detectors in time



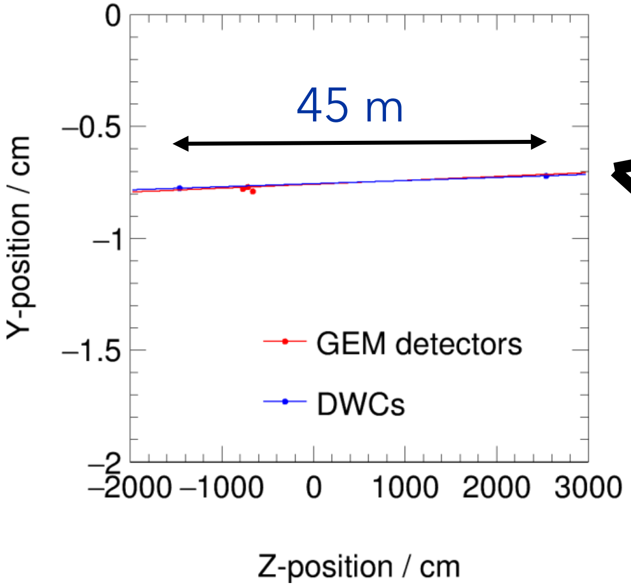
Positions of matched interactions (compatible with scintillators from NA61 trigger-logic)

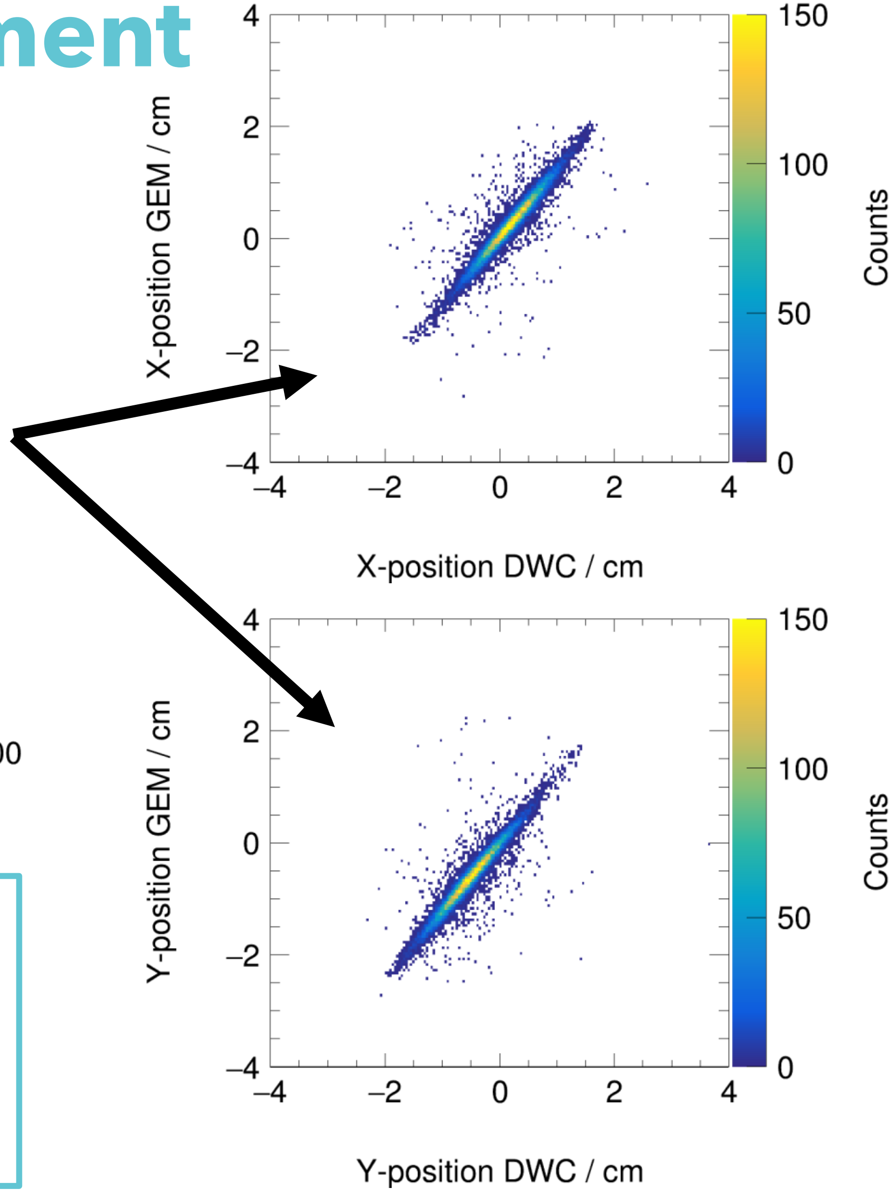
Event matching:
Position and alignment

- 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]





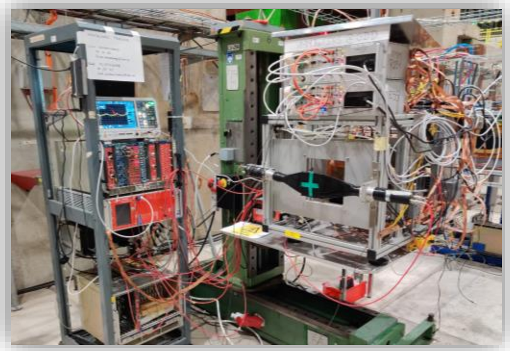
Successful integration of RD51 VMM3a/SRS beam telescope into NA61/SHINE

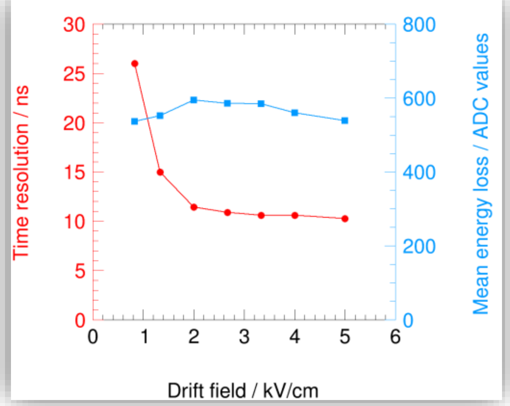
Data used for physics analysis

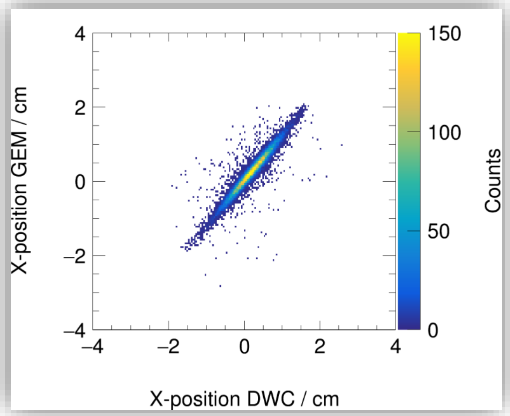
Summary and outlook

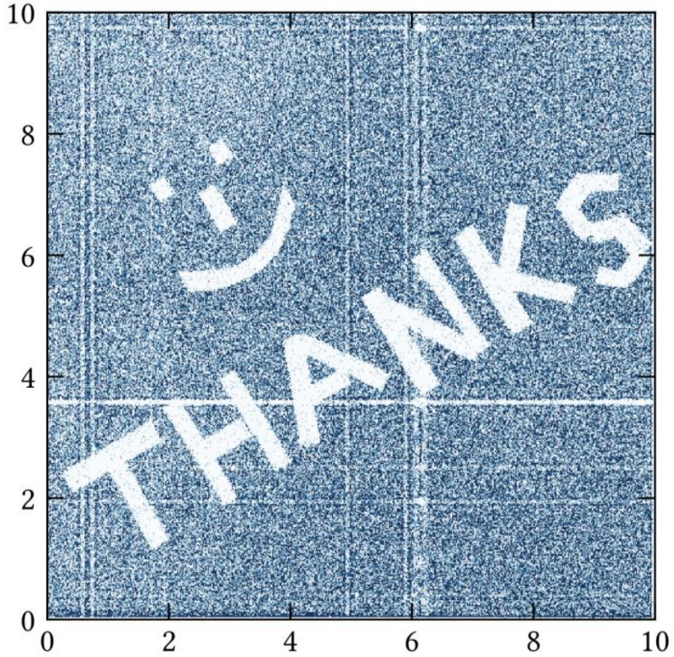
- The GEM-based **beam telescope of RD51** with VMM3a/SRS readout allows studying **time** resolution, **position** resolution and **energy** behaviour **simultaneously**
- **Particle beams with up to 1 MHz** interaction rate can be recorded
- Various detector technologies (not limited to MPGDs) can be read out
- **µRWELL** studied in view of **building a third telescope**
- **Successfully operated as part of the NA61/SHINE** experiment

- Currently **full self-triggered:** implement **externally triggered mode** to achieve lower thresholds
- Started efforts on **distributed system:** increase telescope's **lever arm** from 1 m to **40 m**
- Integration into other experiments started (e.g. with colleagues from NA64 @ CERN or P2 @ Saclay and Mainz)









for your attention!

SPONSORED BY THE
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EP R&D

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

Back-up slides

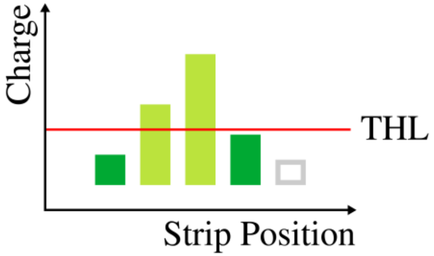
Improving the spatial resolution

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

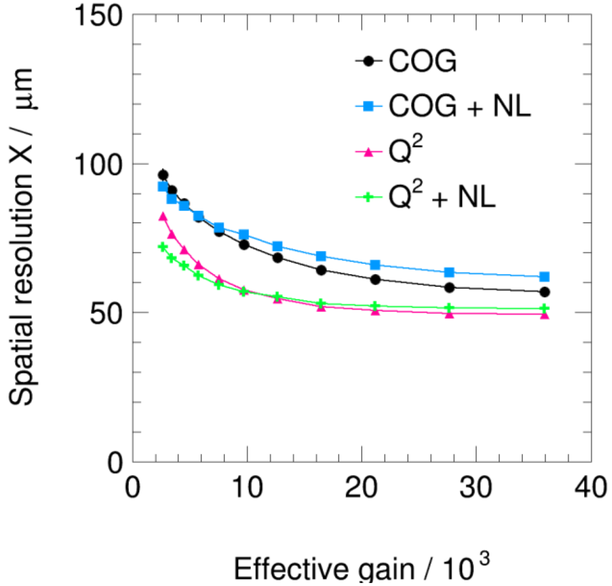
$$x = \frac{\sum_i Q_i^n x_i}{\sum_i Q_i^n} \quad n = 2$$

Review of COG systematics and modifications (MPGD2022): Igor Smirnov: *Algebraic methods for reconstruction of coordinates in strip detectors*

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



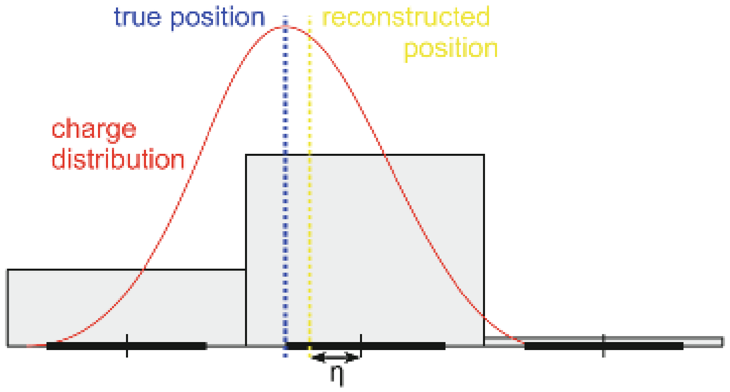
Example @ 1.5 fC THL



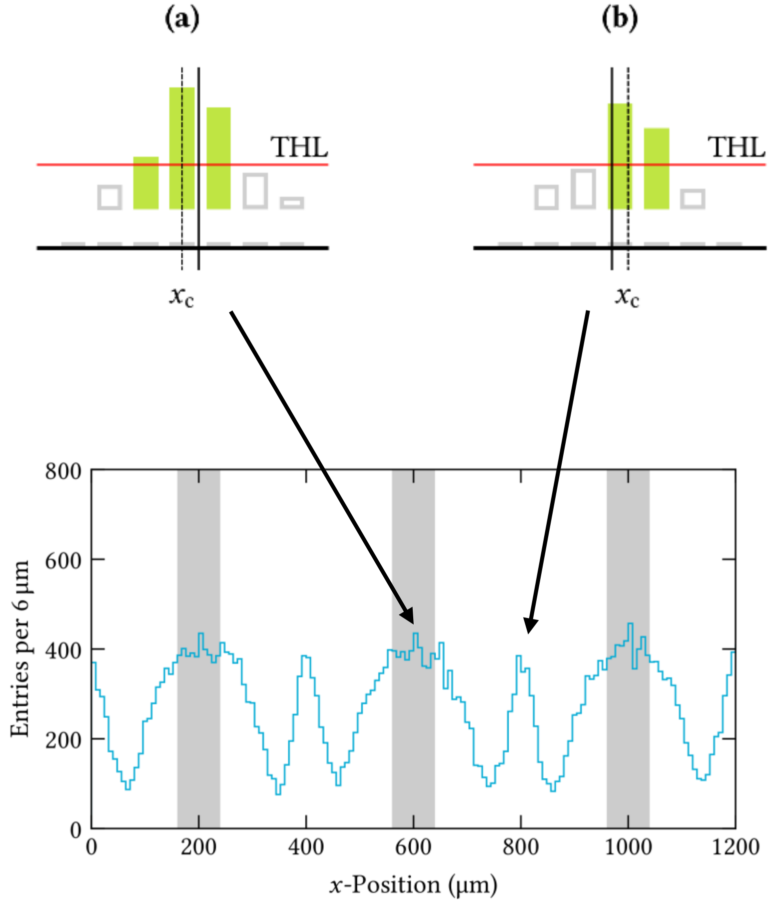
Scanned: THL range from 1.5 fC to 5.5 fC
- **Q² improves spatial resolution all the time**
- NL only at low signal-to-threshold ratio

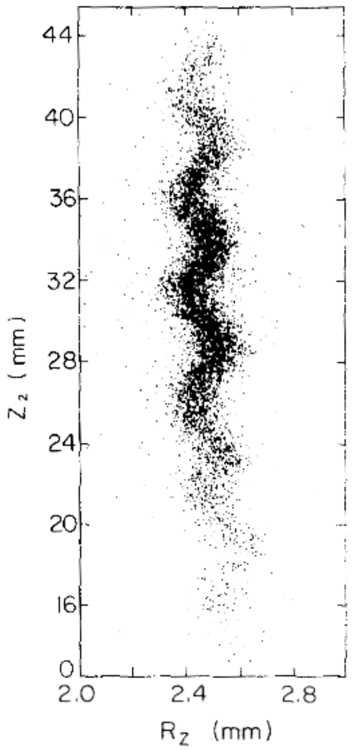
[1] NIM A **1011** (2021) 165576 [2] arXiv: 2302.08330

Modulation of readout pattern



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



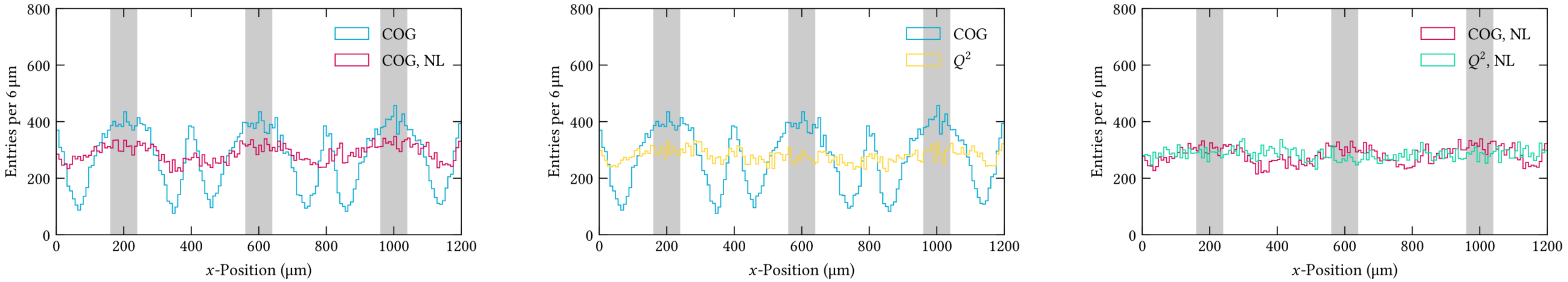


NIM **196** (1982) 451-462

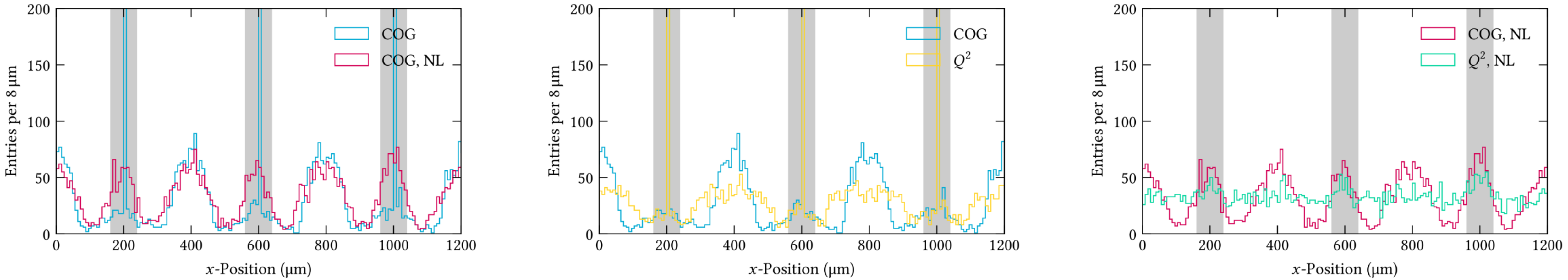
[1] NIM A **1011** (2021) 165576

Modulation of readout pattern

X-rays



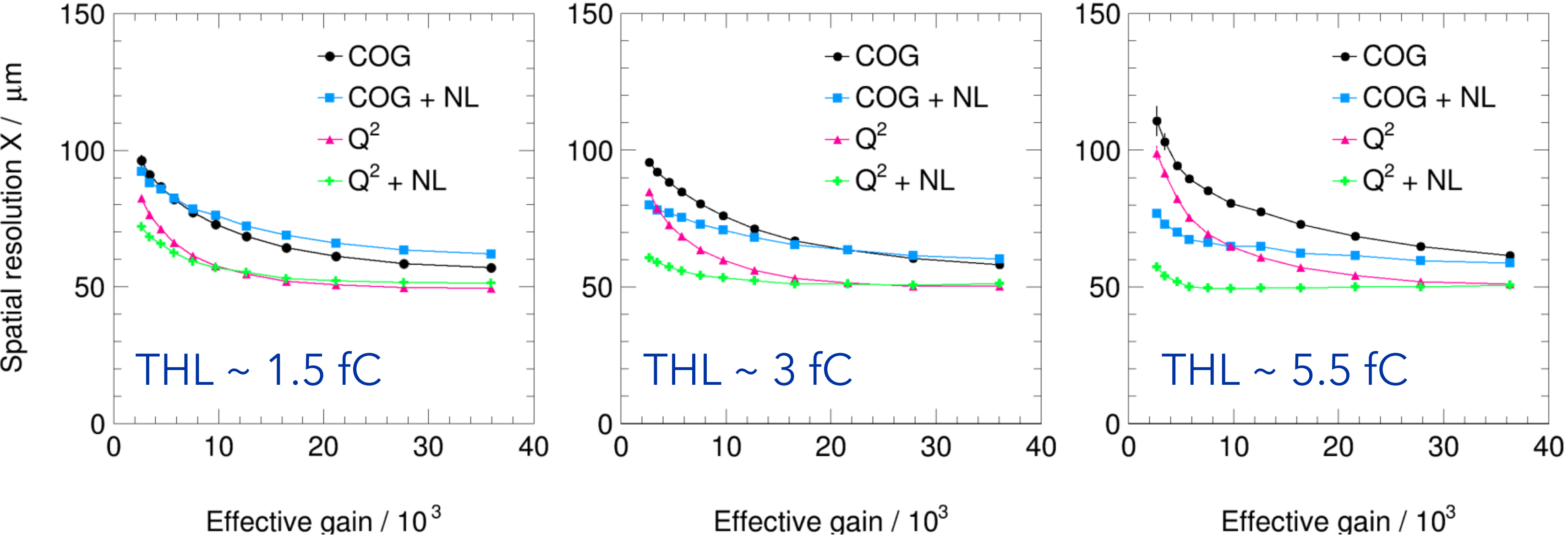
MIPs



[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)