MPGD developments at CERN's Gaseous Detector Development laboratory

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CPAD, October 2026

Content

Pixellated readout
- Integrating pixellated readout ASICs with MPGDs

Optical readout
- Beam monitoring with fast CMOS cameras
- SiPM readout of MPGDs

Precise timing
- PICOSEC Micromegas prototype modules
- Photocathode studies

Readout Electronics for Gaseous Detectors

Modeling and Simulation

Pixellated readout

Embedding of Timepix4 in MPGD

Timepix has been previously used to read out MPGDs: e.g. **GEMPix** (10.1016/j.radmeas.2020.106421)

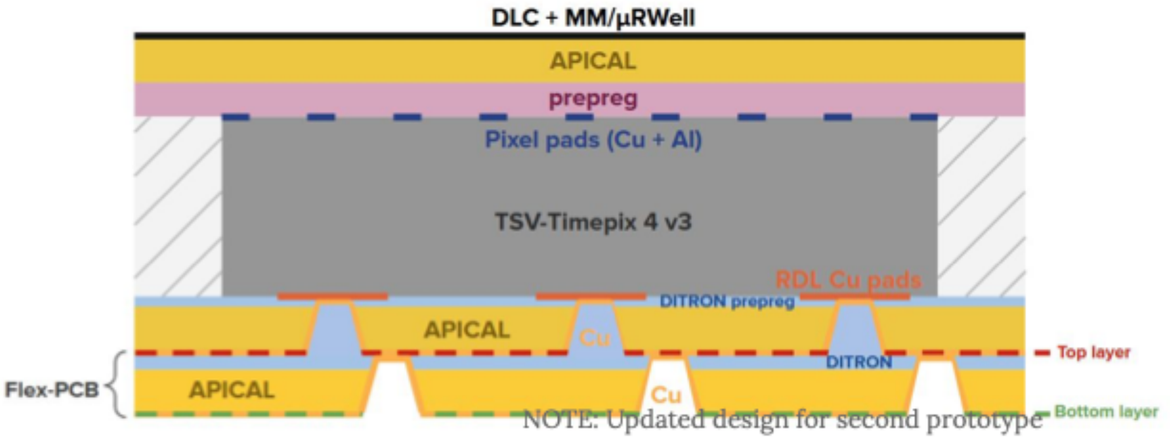
Optimising signal induction by **integrating amplification structure** directly with the front end readout ASIC

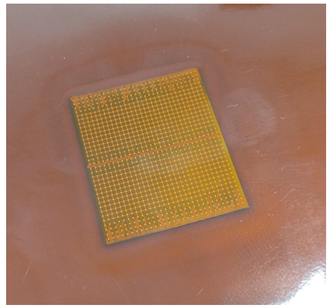
Timepix4 is an enabling technology by allowing 4-side tilability and backside readout (TSVs)

Use of **diamond-like carbon (DLC)** as resistive anode on top of Timepix4 readout structure:

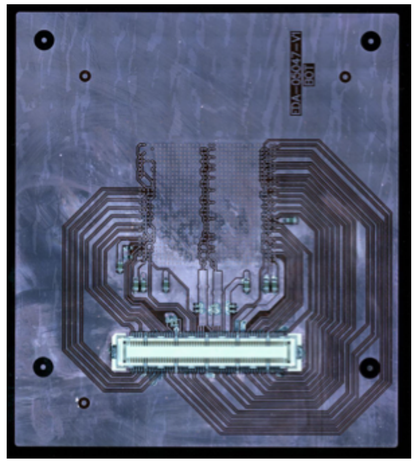
- Deposition at CERN MicroPattern Technologies (MPT) workshop
- Discharge protection and signal spreading

Cross-section of Timepix4 embedded in MPGD structure:





Encapsulation test of Timepix4 for µRWELL integration



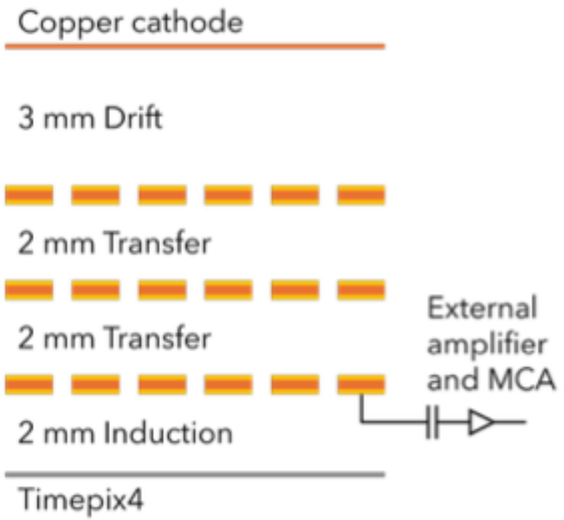
Eliska Jelinkova. David Marques, DRD1 Collaboration Meeting June 2026
https://indico.cern.ch/event/1662850/contributions/7133781/attachments/3304919/5913930/Coimbra (1).pdf

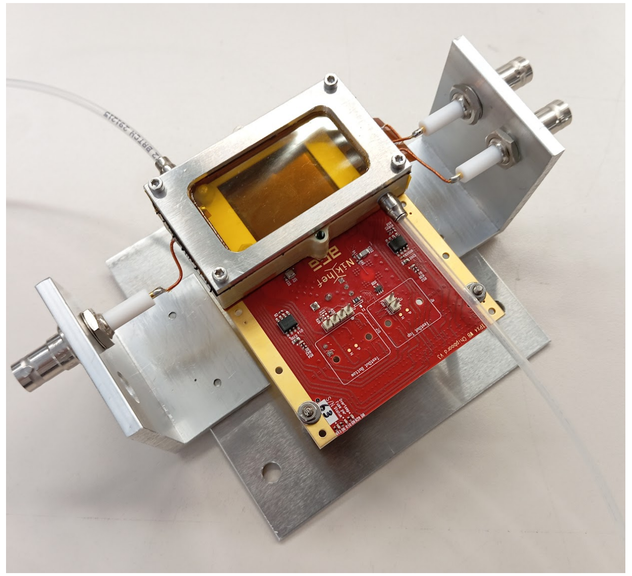
GEMPix4

Coupling triple GEM with Timepix4 readout
Intermediate step towards integration of TImepix4 directly with amplification structure

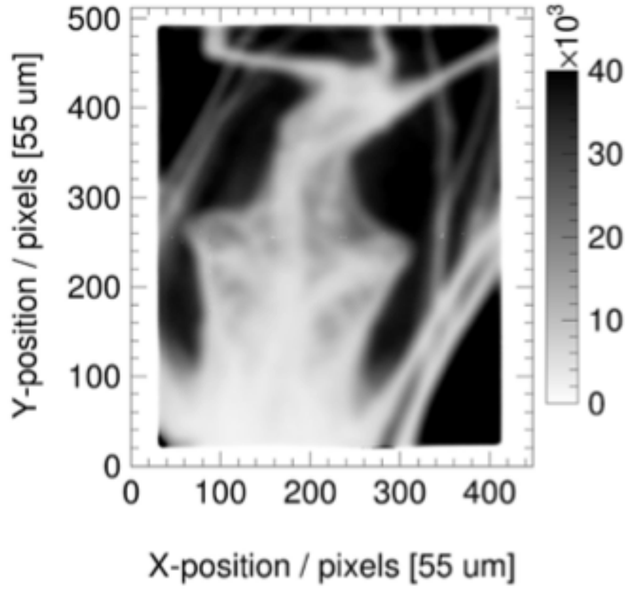
Large clusters due to diffusion in triple GEM stack

High spatial resolution achieved for single particle detection and Xray imaging





GEMPix4: triple GEM with Timepix4 readout



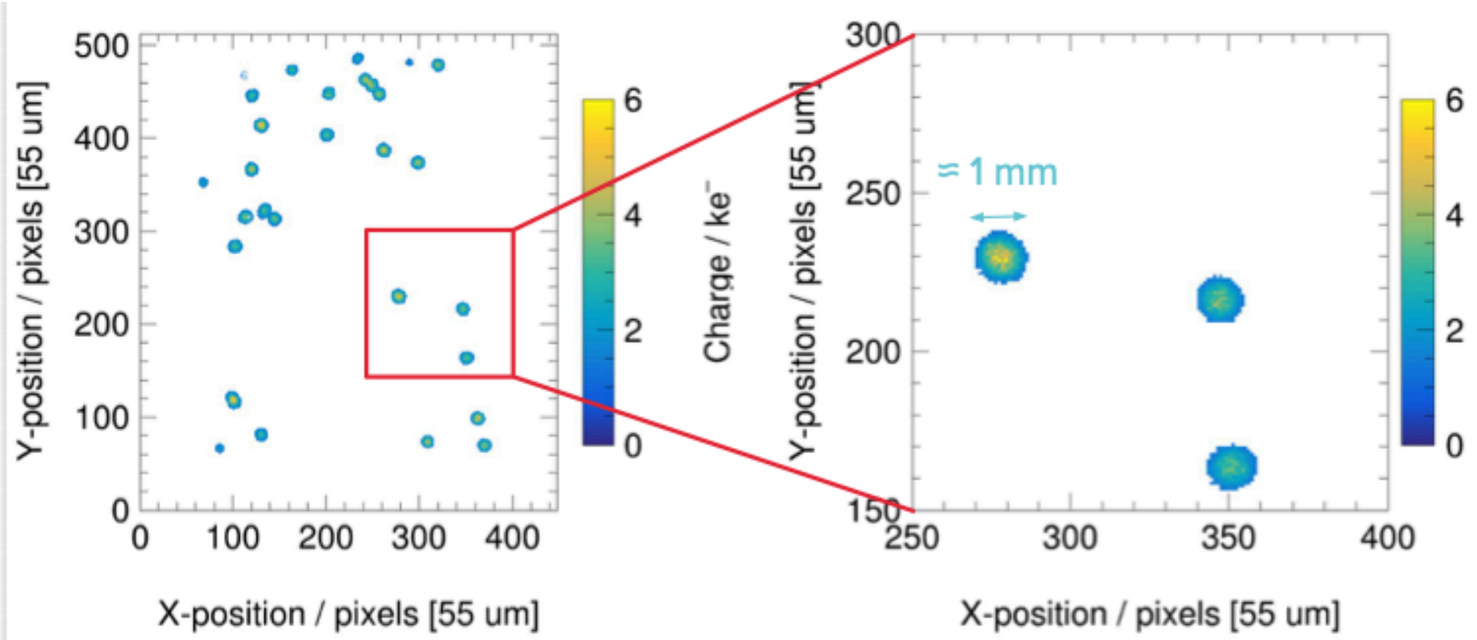
L. Scharenberg et al.
https://indico.cern.ch/event/1386009/contributions/6279112/attachments/3018409/5324403/mpgd-timepix4_vci2025_lucian-scharenberg.pdf

GEMPix4

Visualisation of individual **soft X-rays from Fe55 source**

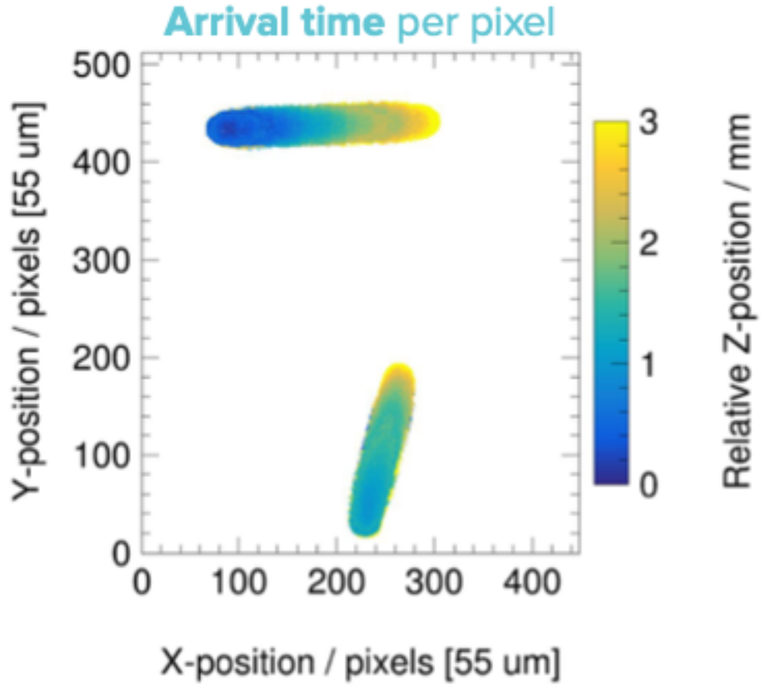
0.2mm photoelectron track length for 6keV X-rays in Ar/CO2 (70/30)

1mm diameter circular events due to diffusion in triple GEM stack



Cosmic rays

Wide, straight tracks with inclination encoded in arrival time differences (color scale)

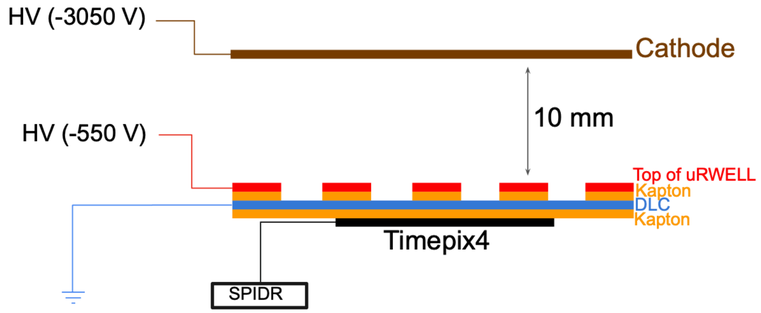


L. Scharenberg et al.
https://indico.cern.ch/event/1386009/contributions/6279112/attachments/3018409/5324403/mpgd-timepix4_vci2025_lucian-scharenberg.pdf

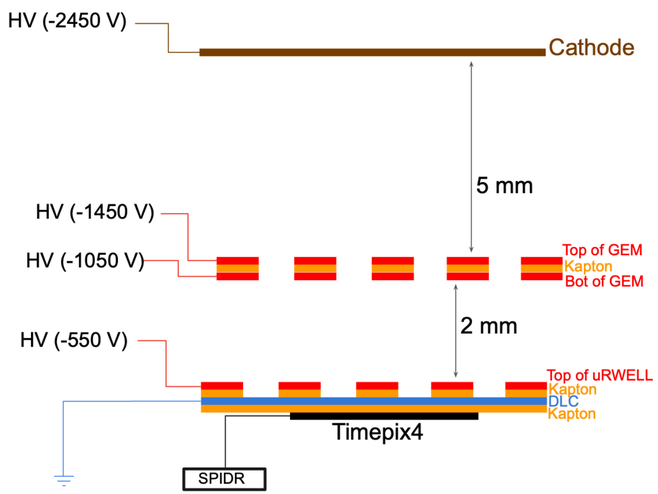
Embedding of Timepix4 in MPGD

Exploring different schemes to readout MPGD structure with Timepix4

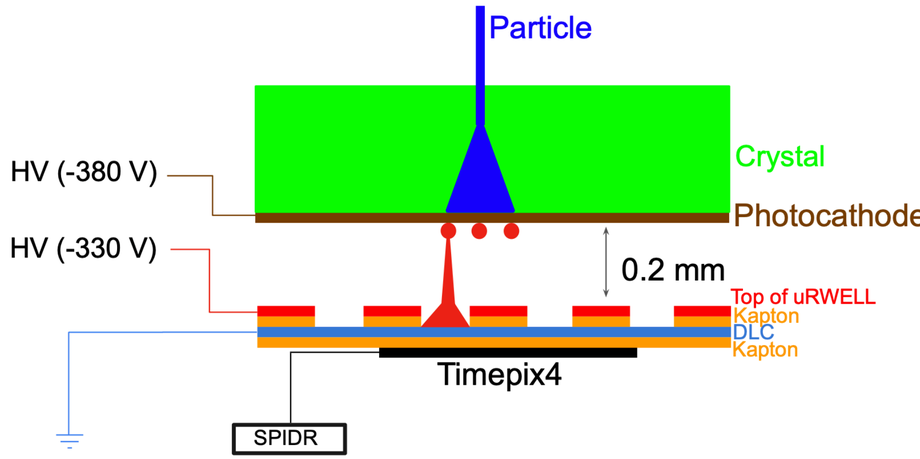
μRWELL + Timepix4



μRWELL + GEM + Timepix4



Picosec μRWELL + Timepix4

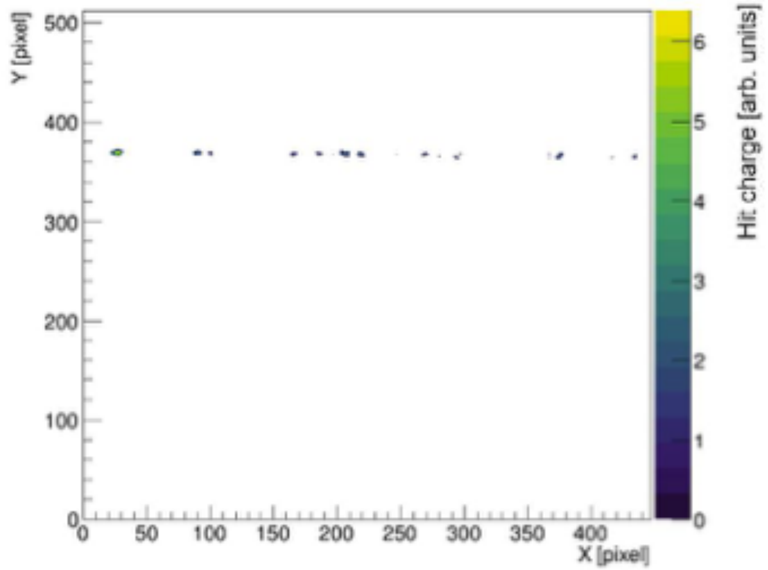


Eliska Jelinkova. David Marques, DRD1 Collaboration Meeting June 2026
https://indico.cern.ch/event/1662850/contributions/7133781/attachments/3304919/5913930/Coimbra (1).pdf

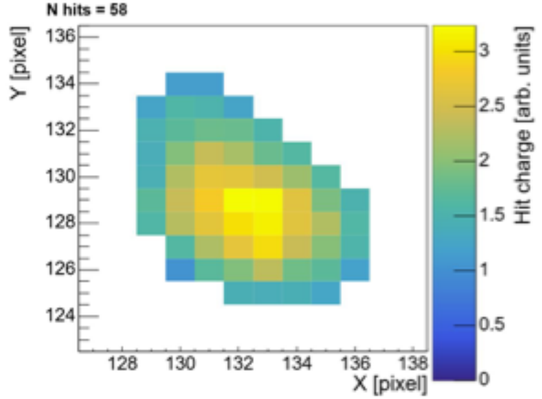
Coupling Timepix4 to μRWELL

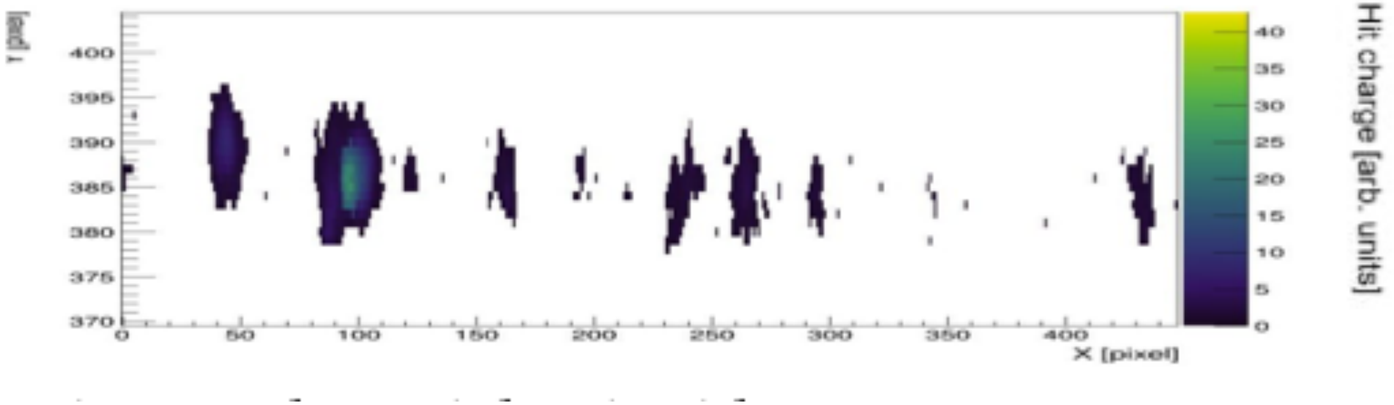
Recording of cluster representing **individual Fe55 Xray** interactions or clusters along **particle tracks** from muon or pion beams

Large clusters with tens of active pixels allow for centre-of-gravity position reconstruction



^{55}Fe cluster example:





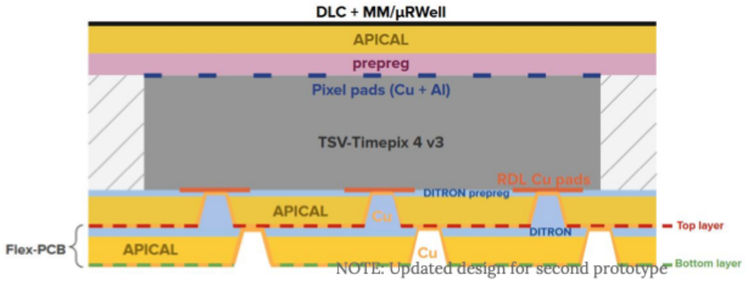
Eliska Jelinkova. David Marques, DRD1 Collaboration Meeting June 2026
https://indico.cern.ch/event/1662850/contributions/7133781/attachments/3304919/5913930/Coimbra (1).pdf

Timepix4 MPGD readout

Current status

- Working prototypes with **mechanically coupled MPGD** and Timepix4 readout
- **Embedding of Timepix4** with μRWELL structure done by CERN MicroPattern Technologies (MPT) workshop: realising new way to contact Timepix4 TSV chip with photolithography techniques

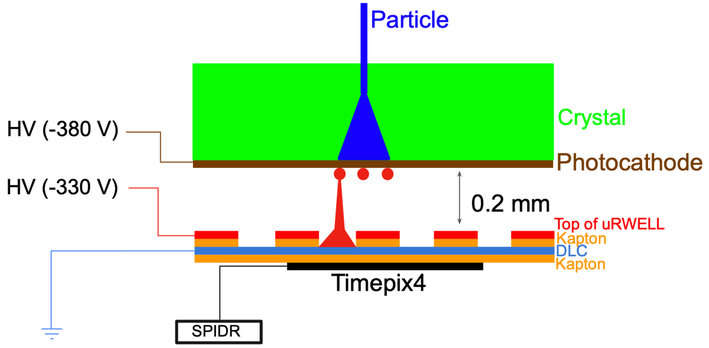
Cross-section of Timepix4 embedded in MPGD structure:



NOTE: Updated design for second prototype

Next steps

- **Multi-chip** Timepix4 readout structure
- **Precise timing** measurements in PICOSEC Micromegas configuration



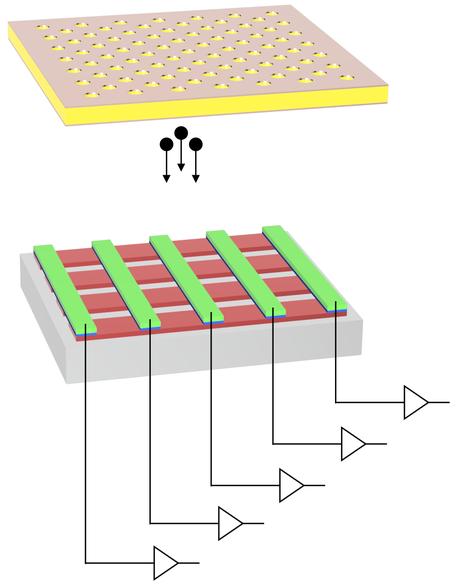
Eliska Jelinkova. David Marques, DRD1 Collaboration Meeting June 2026
https://indico.cern.ch/event/1662850/contributions/7133781/attachments/3304919/5913930/Coimbra (1).pdf

Optical readout

Readout of MicroPattern Gaseous Detectors

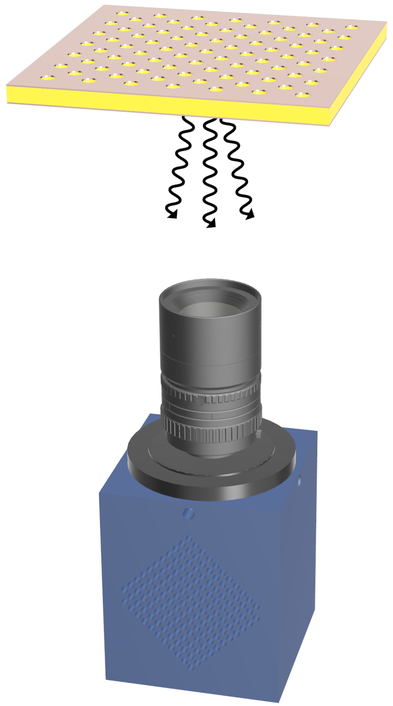
Electronic readout

Recording induced electronic signals with readout electronics

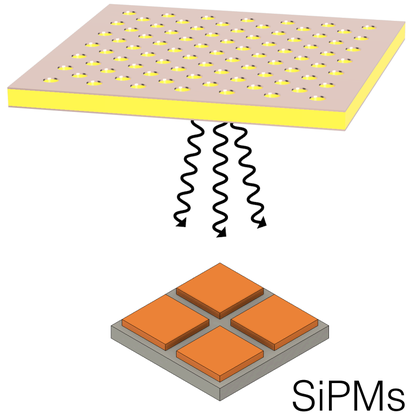


Optical readout

Recording scintillation light with imaging sensors



SiPM readout of secondary scintillation



Integrated imaging approach

Intuitive pixelated readout with **megapixel imaging sensors**

High spatial **resolution**

Lenses and mirrors to enable adjustable magnification and camera location

Limited **frame rate**

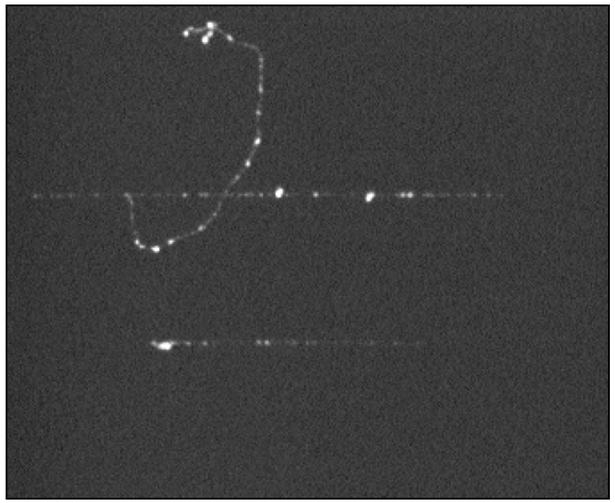
Low radiation hardness of imaging sensors

Matching of **emission spectrum** to image sensor QE (e.g. CF_4-based gas mixtures or wavelength shifters)

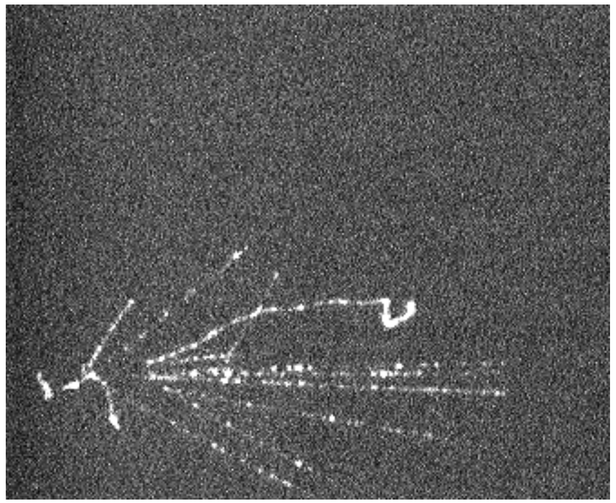
Schematics not drawn to scale

Particle track images

Event-by-event monitoring

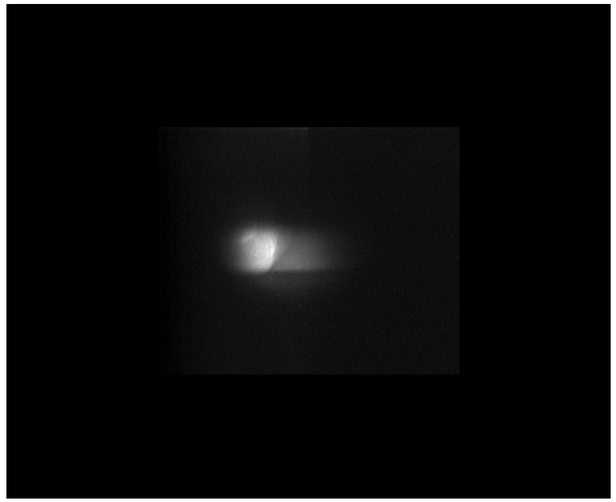


Muon tracks with δ-ray

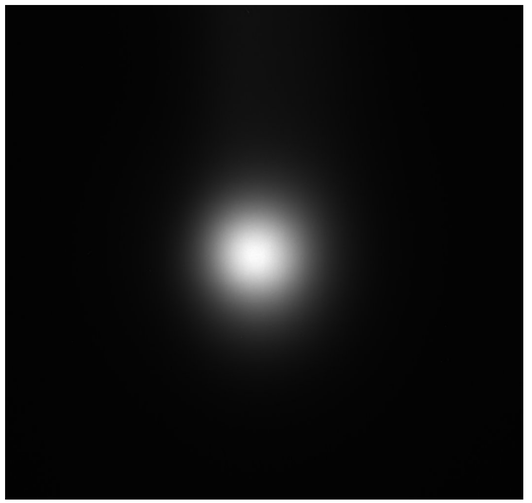


Hadronic shower

Integrated imaging



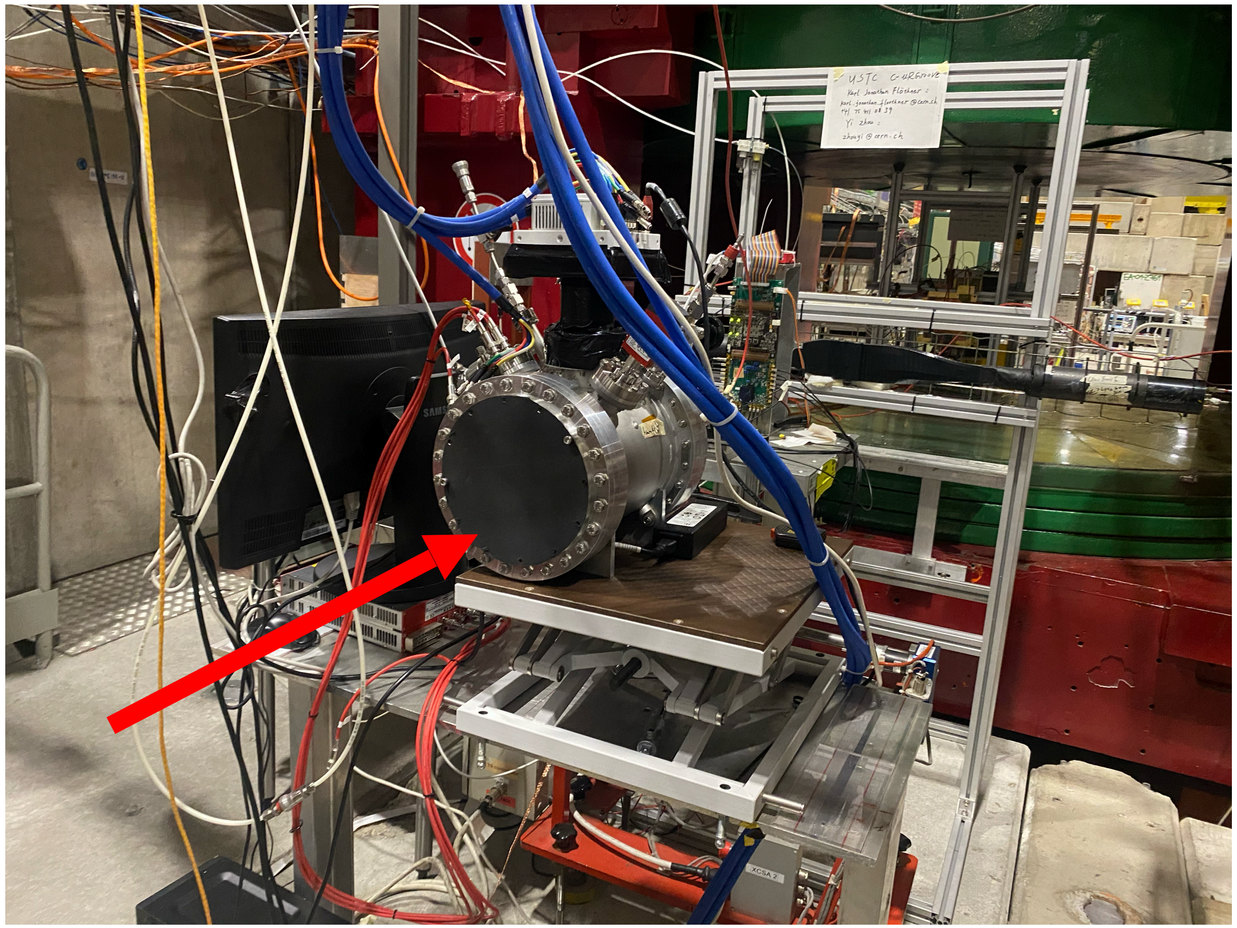
Pion beam profile

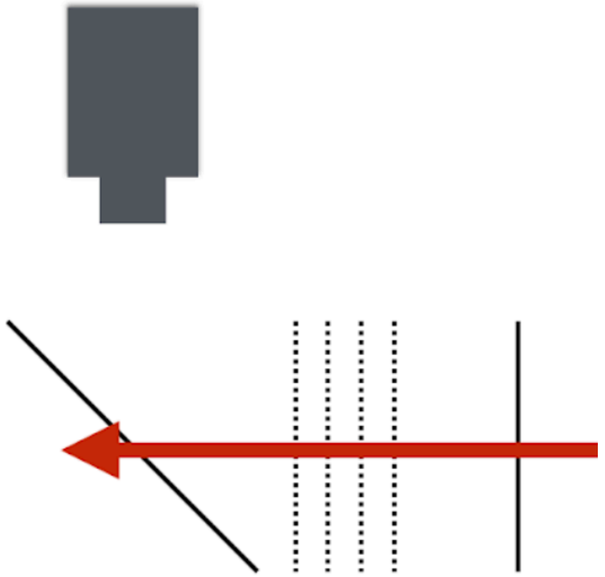


Proton beam profile

10cm x 10cm active area

DRD1 SPS H4 test beam campaign 2025



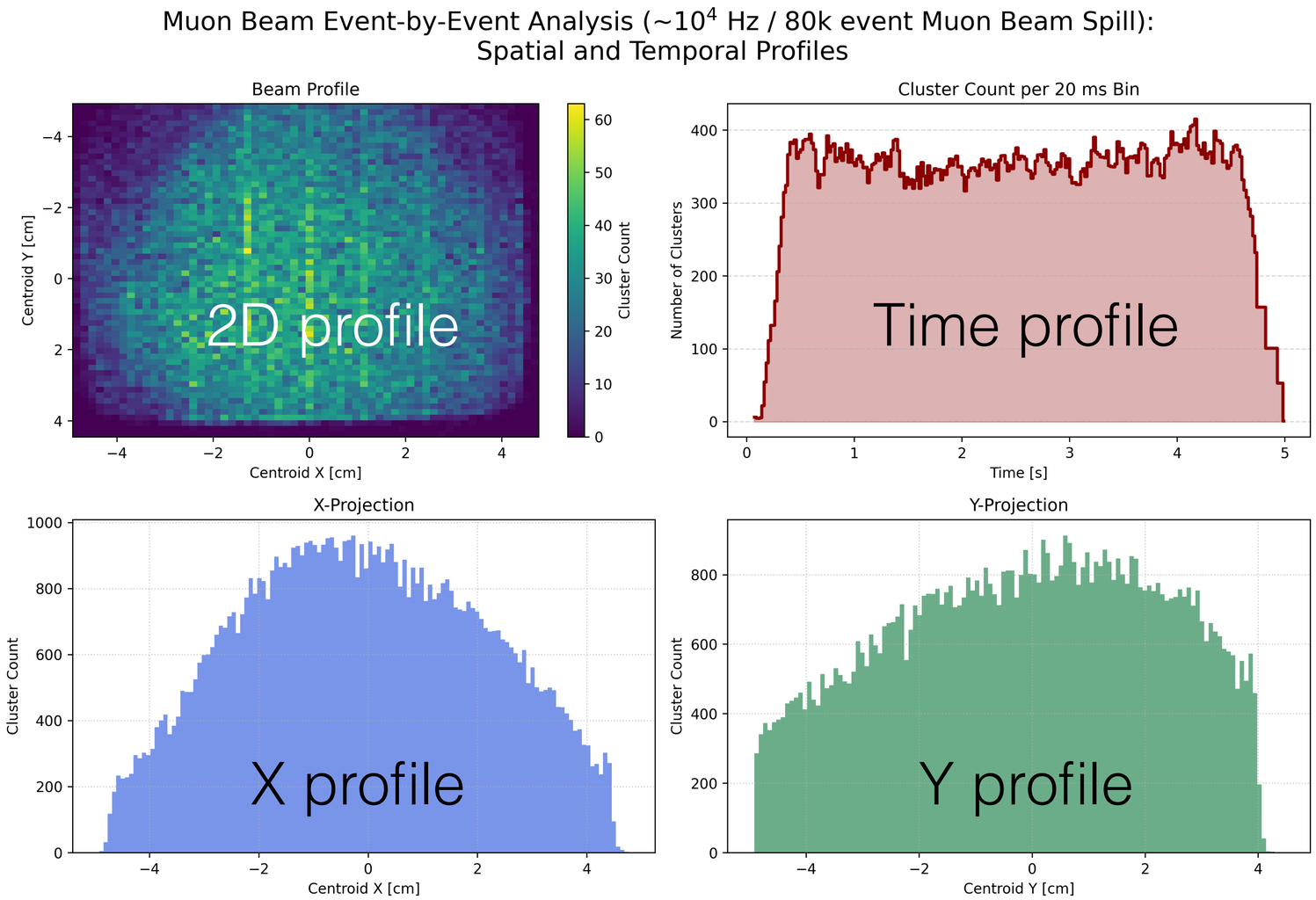


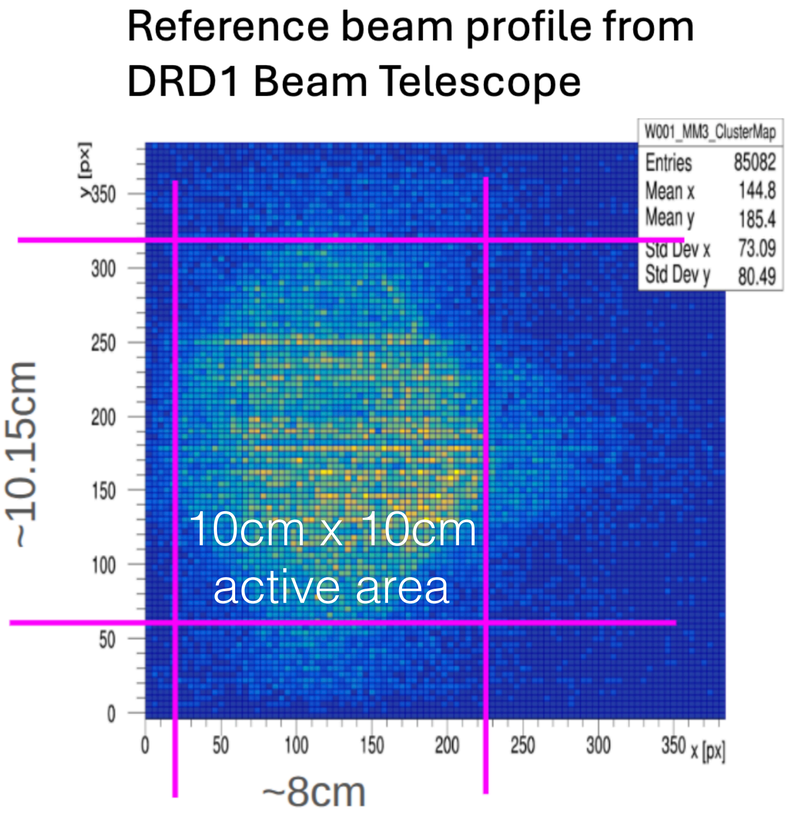
Phantom S710



- 1 megapixel CMOS sensor
- 12 bit depth
- **7 kfps** at 1280 x 800
- >30 e- read noise

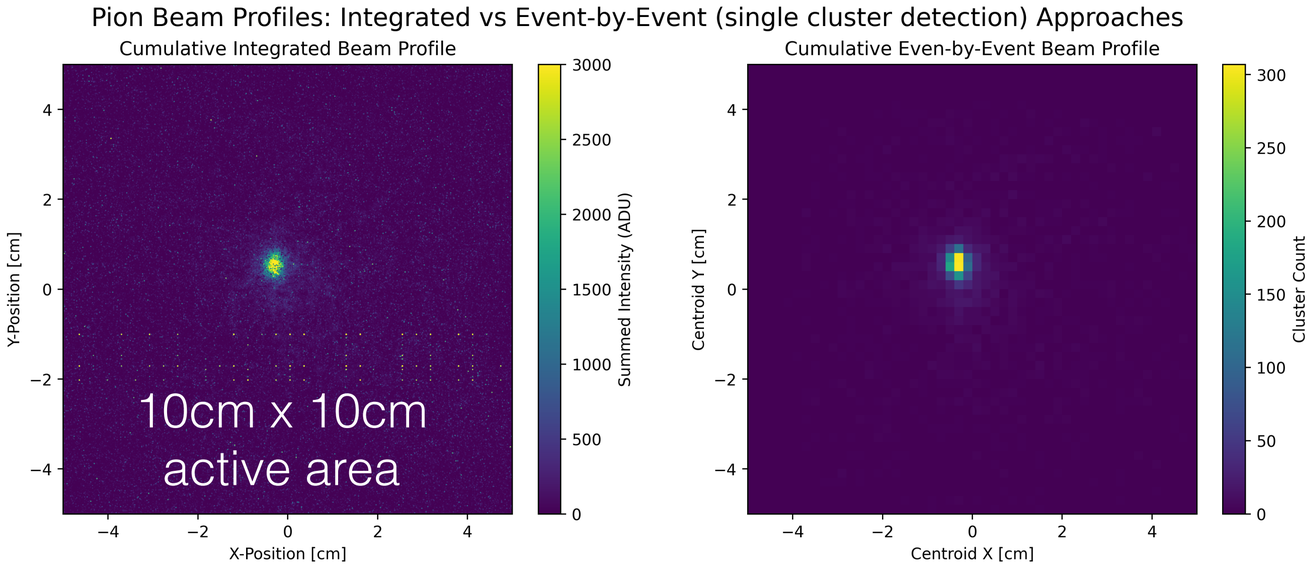
Muon beam profile recording





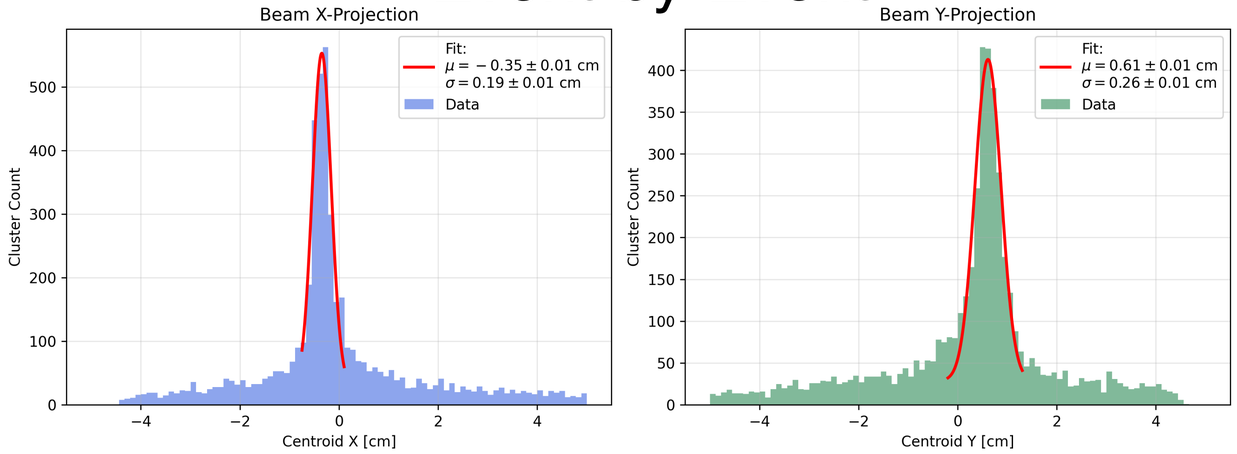
Pion beam profile recording

One low rate spill ~ 10^3 Hz, 2 ms exp. time

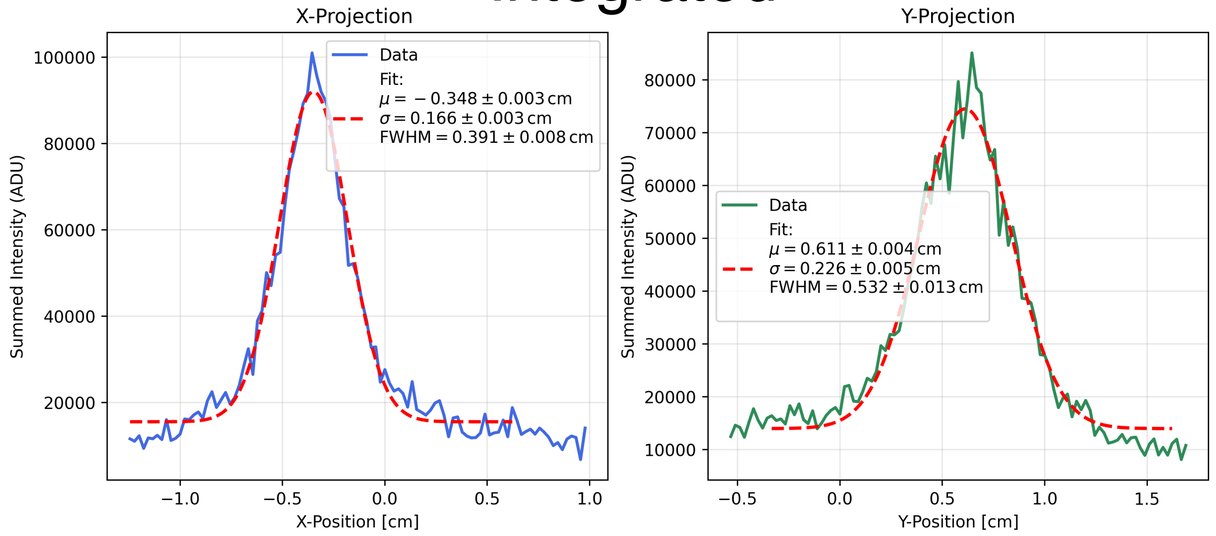


Reference: 5.5k events
Detected: 5k events

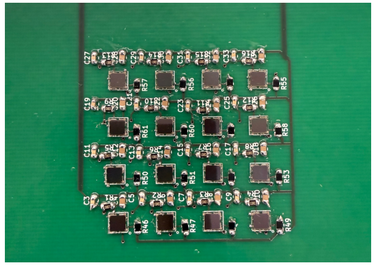
Event-by-Event



Integrated

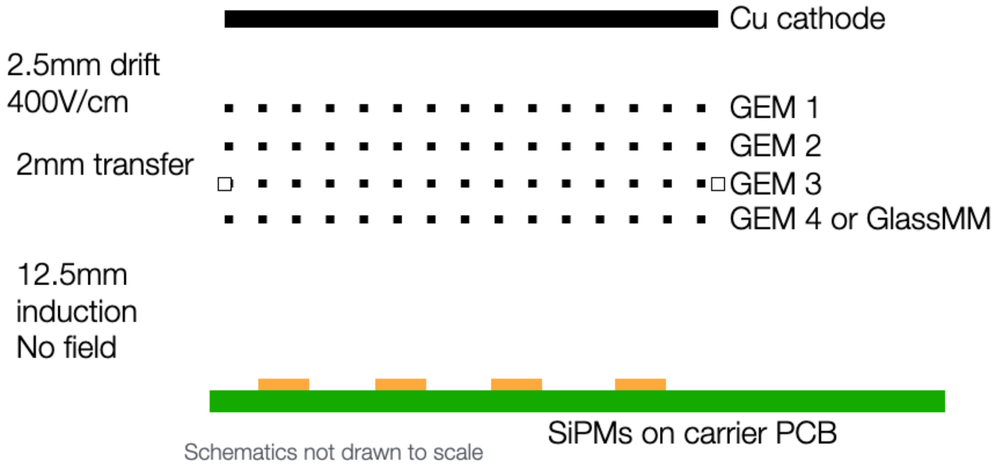


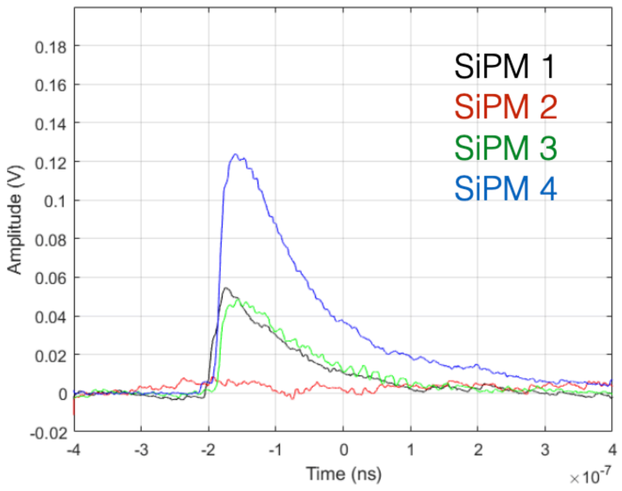
SiPM readout of GEMs and Micromegas

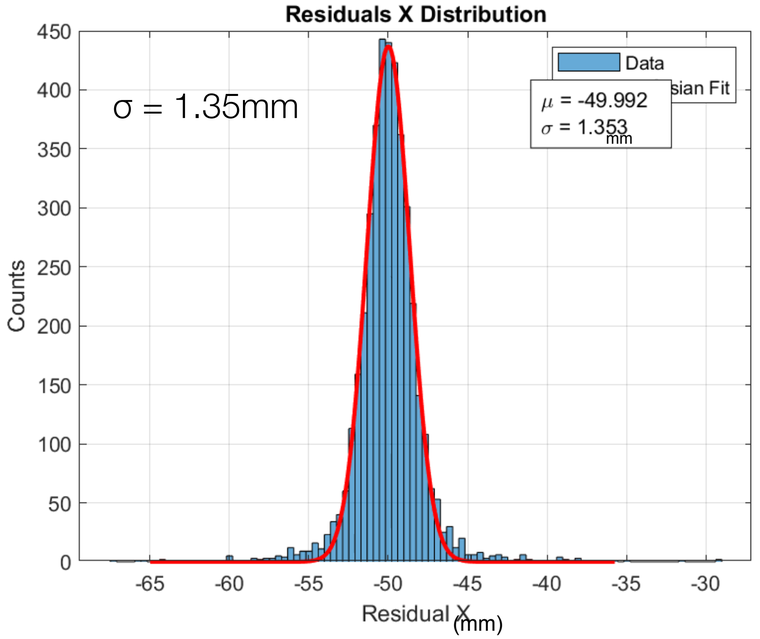


Active area was scanned with trigger MCP, amplitudes from all 16 SiPMs were recorded and used for COG reconstruction

For residuals, center of active area was selected (cut on tracker) and only events with >=4 active SiPMs over threshold were included



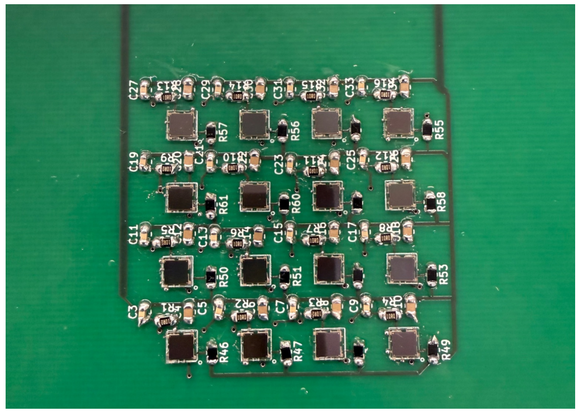




Optical readout

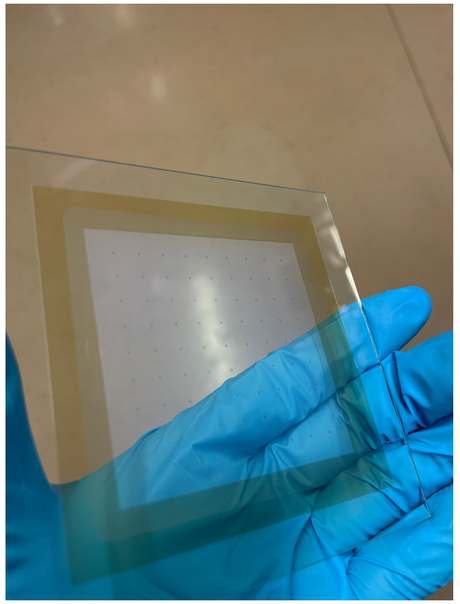
Current status

- Evaluated **optical beam monitoring** for muon, pion and proton beam (SPS, hadron therapy facility)
- Demonstrated **high-speed optical readout** with CMOS camera
- SiPM readout of different MPGD structures
- Optical readout with **TPB as solid wavelength shifter**



Next steps

- Beam profile and **time structure** monitoring of electron beams (CLEAR, CHUV Lausanne)
- **Medical beam monitoring** applications
- Timing measurements with SiPMs
- Exploration of alternative gas mixtures



Precise timing

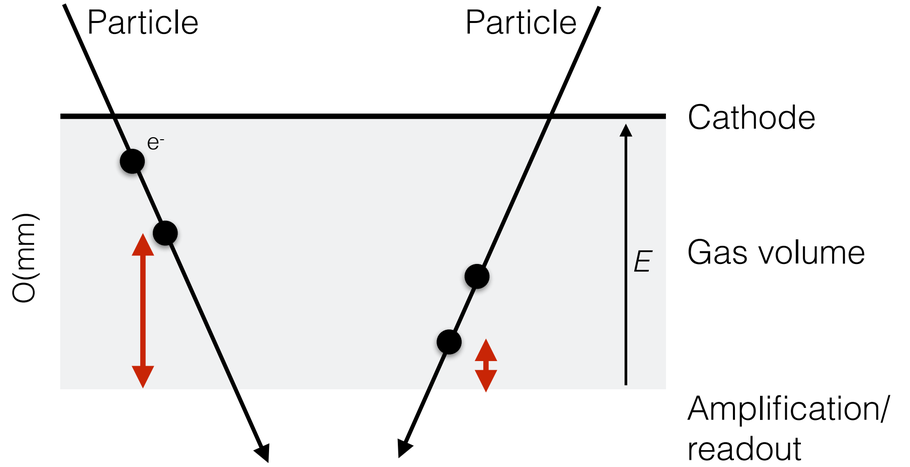
Timing limitations of gaseous detectors

Conventional gaseous detectors

Ionisation of gas in active volume

Primary electrons produced by ionisation along particle trajectory in drift region

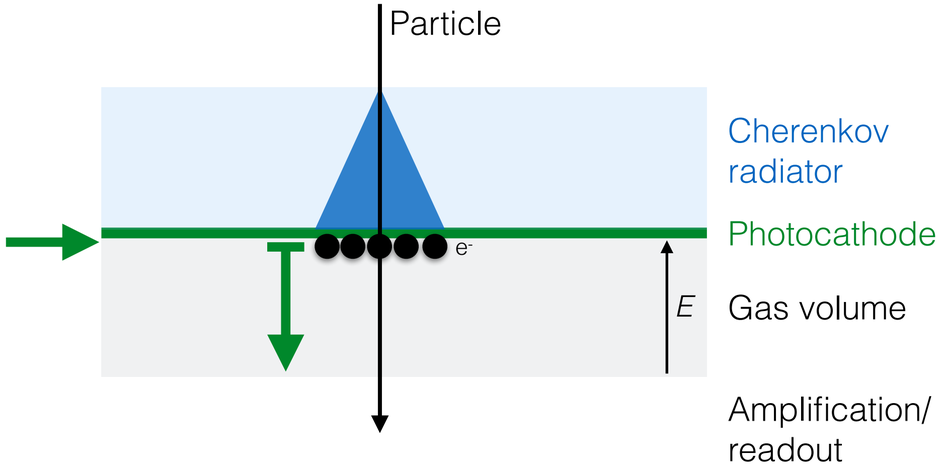
Drift distance differences on the order of millimetres
→ **Timing jitter of ≈ ns**



PICOSEC Micromegas precise timing detectors

Cherenkov light emission + photocathode
or solid secondary converter layer

Primary electrons at **well-defined location & time**
→ **Timing jitter of ≈ tens of ps**



Schematic not drawn to scale

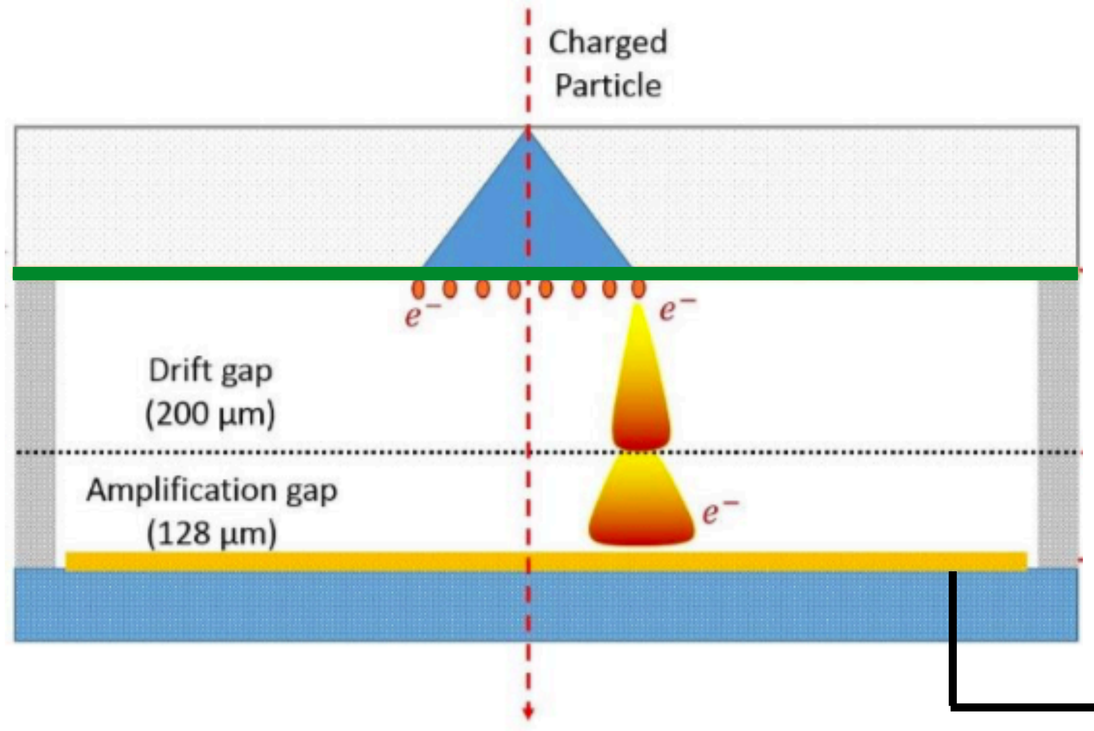
PICOSEC detection concept

Precise timing with Micromegas

PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A (903), 2018, https://doi.org/10.1016/j.nima.2018.04.033

Cherenkov radiator
(3 mm MgF_2)

Light to charge conversion
Photocathode (CsI)



Preamplification
Drift gap

Amplification
Micromegas

2-stage amplification

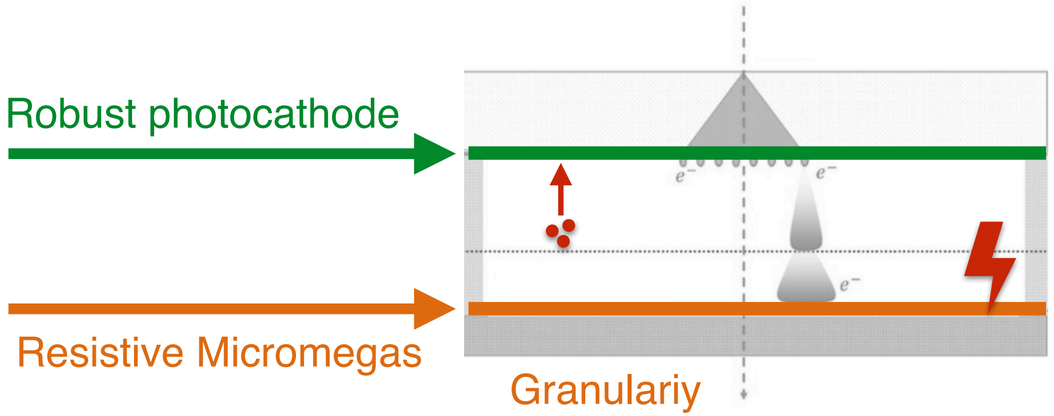
Induced signal readout

Gas mixture: 80% Ne + 10% C_2H_6 + 10% CF_4
at ambient pressure

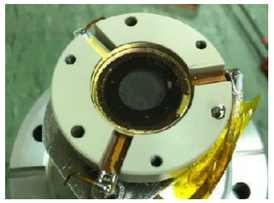
Schematic not drawn to scale
X. Wang et al., Study of DLC photocathode for PICOSEC detector, RD51 collaboration meeting, October 2018

Towards a robust, large-area detector

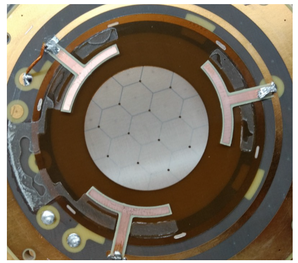
Robustness
- Resistive Micromegas (DLC)
- Robust photocathodes



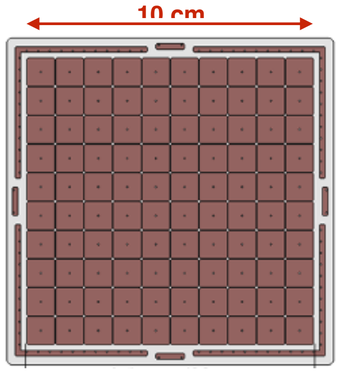
Tileable detector modules



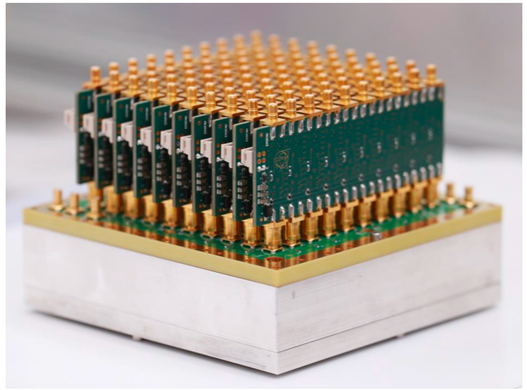
Single pad (2016)
ø1 cm



Multi pad (2017)
⬡ 1 cm



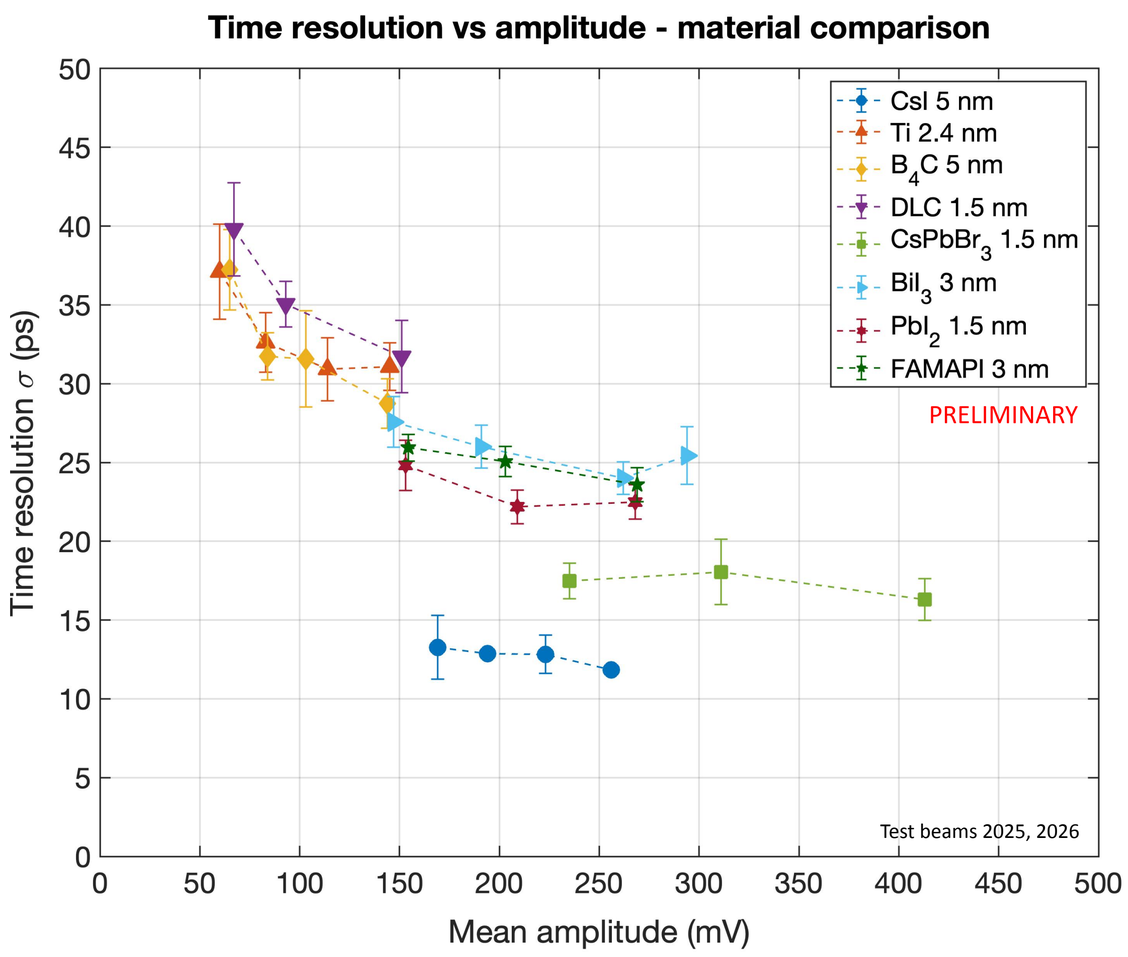
10x10 module
▫ 1 cm

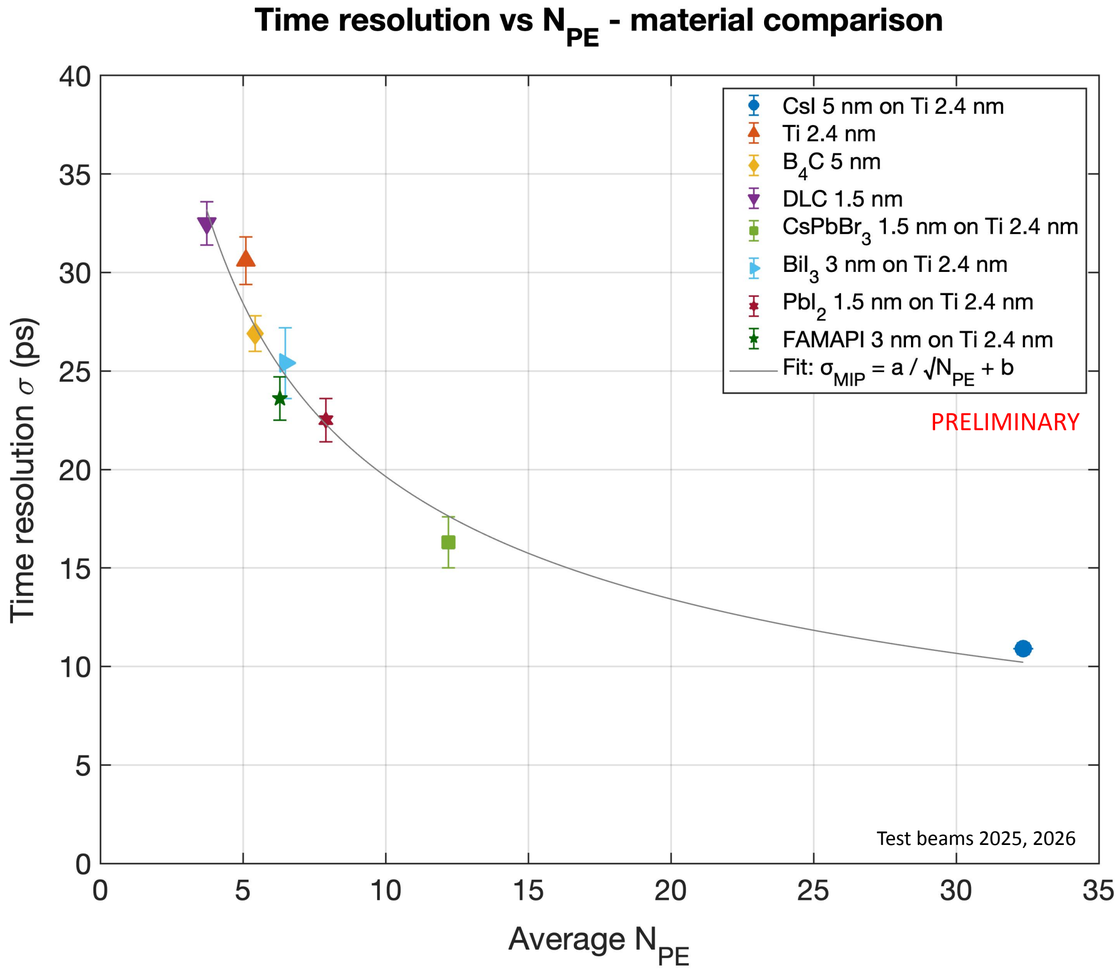


Schematic not drawn to scale

Photocathode characterisation

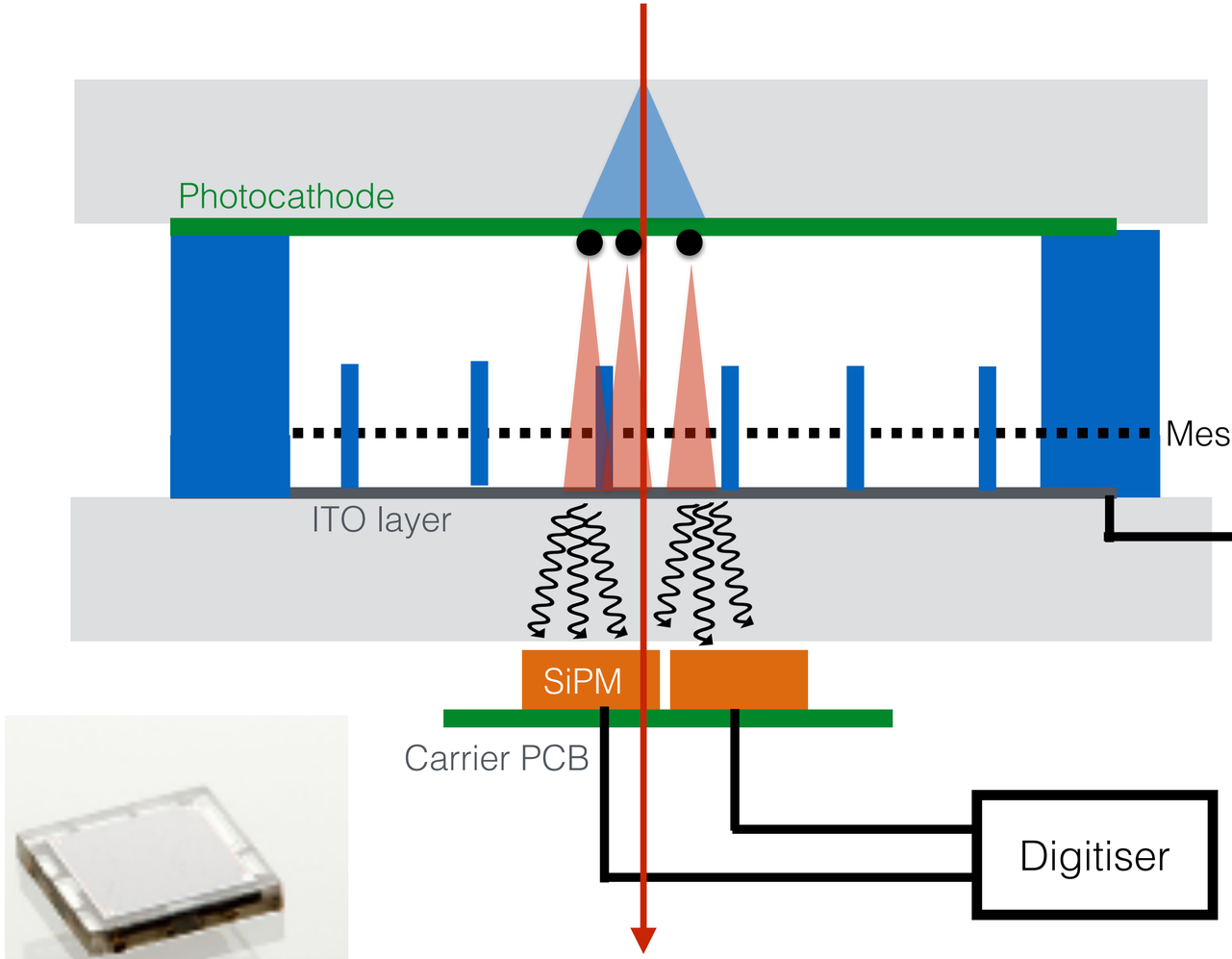
For each material, the optimal thickness was selected and compared with other photocathodes

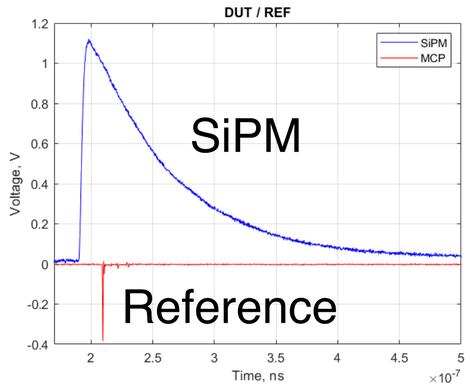




Electronic + optical PICOSEC readout

- Read out electronic signal and optical signal simultaneously
- Electronic signal used for timing
- Optical signal is slower (scintillation time constant) and can be used for position reconstruction with segmented readout with SiPMs



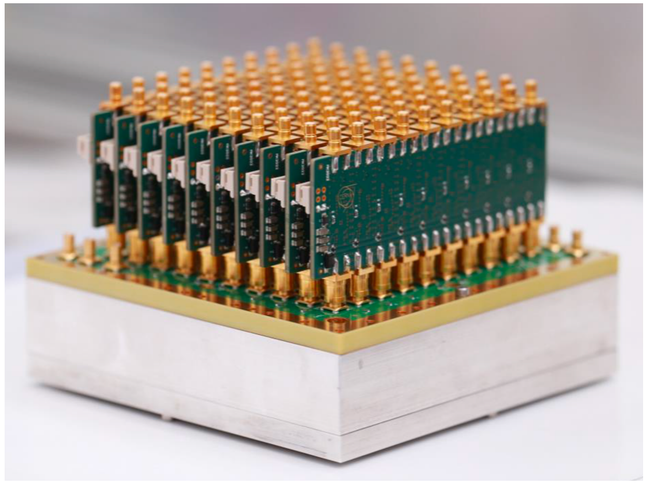


Schematic not drawn to scale

Precise timing: PICOSEC Micromegas

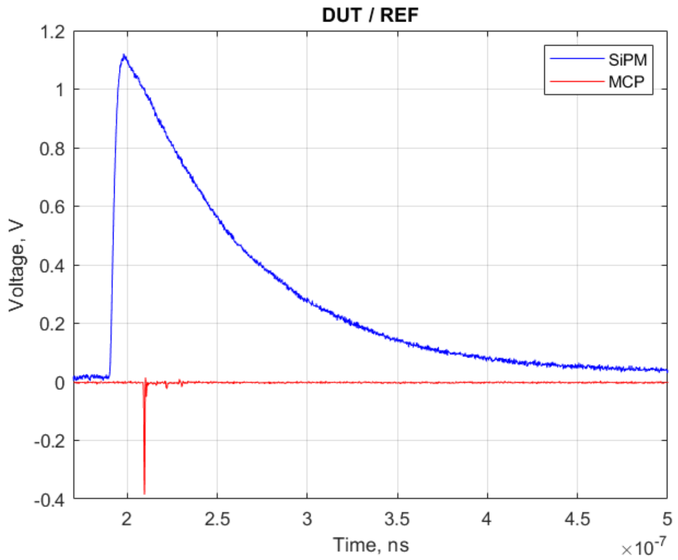
Current status

- **Optimisation** of single channel precise timing prototypes
- Tileable multi-channel module
- **High-rate Micromegas** layout with double-DLC anode
- Dedicated precise timing **readout electronics**
- **Photocathode studies** and evaluation of robust materials



Next steps

- Lower material budget detector build up options
- Evaluation of **novel photocathode materials**
- **SiPM readout** for precise timing and spatial resolution



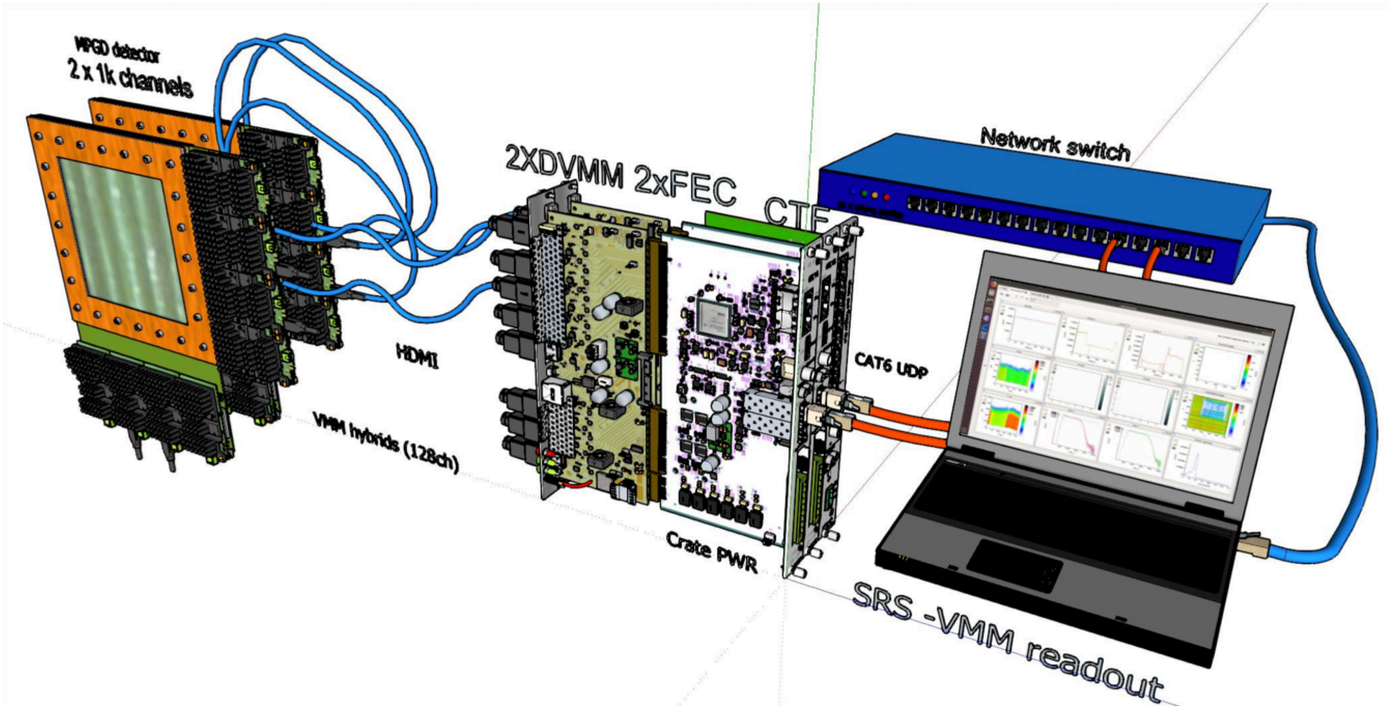
Readout Electronics for Gaseous Detectors

Scalable readout system (SRS)

The **scalable readout system** is a versatile readout system for gas and photon detectors which consist of **front end hybrids**, **common FEC** cards and readout software.

Multiple front end ASICs have been implemented in the SRS over the years including the APV25 chip and the VMM3a FE ASIC as well as SAMPA.

Scalable Readout System (SRS) was developed in the **RD51 collaboration** and is now widely used in the gaseous detector community. Developments continue in the **DRD1 collaboration** with multiple groups participating in developments of future capabilities and hardware.

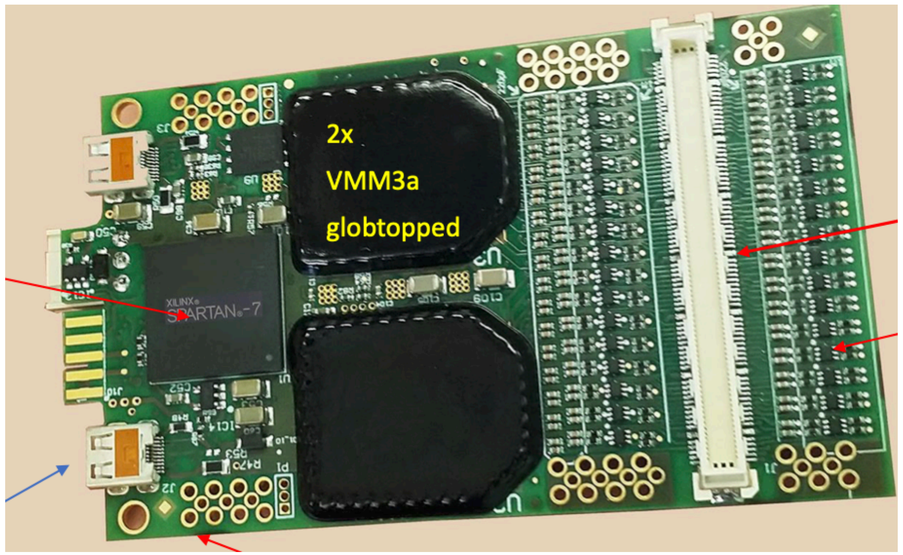


Hans Muller, https://indico.cern.ch/event/1360282/contributions/5786568/attachments/2790914/4867304/Scalable Readout System for DRD1.pdf
Hans Muller, https://indico.cern.ch/event/1632132/contributions/6960227/

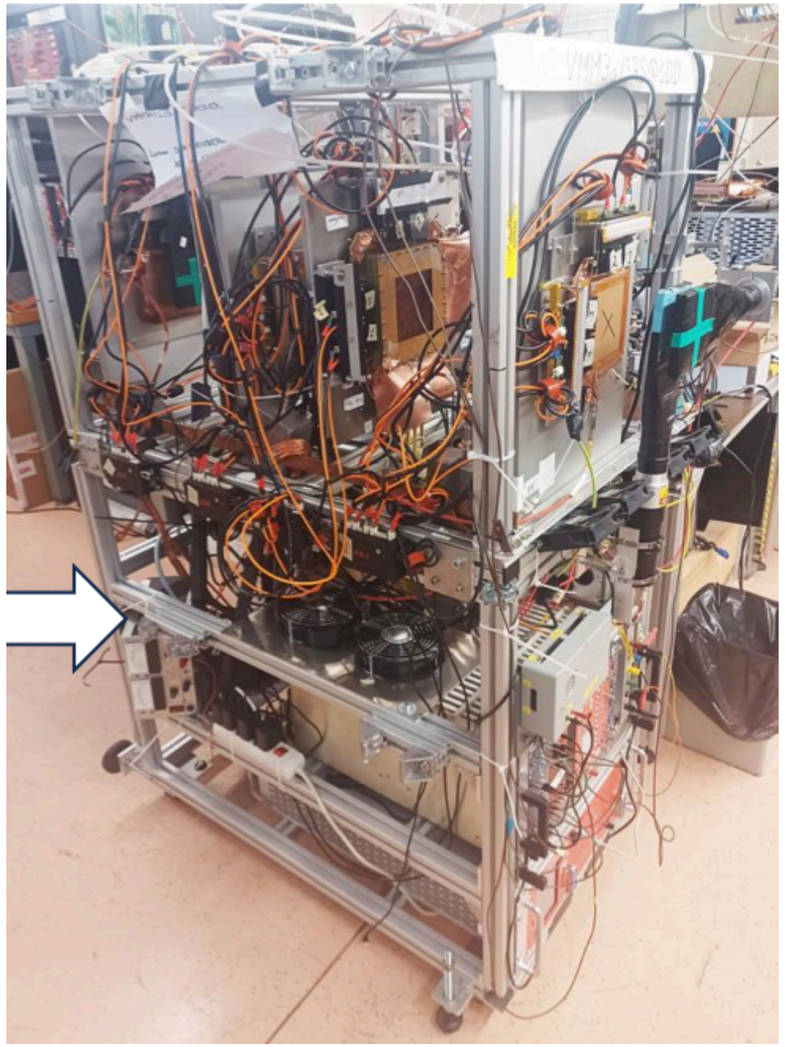
SRS + VMM3a

VMM3a has been integrated in the SRS as a baseline readout chip for **high-rate self-triggered readout**

Multiple telescopes based on VMM3a have been built including the DRD1 VMM3a GEM telescope used to test different DUTs during DRD1 test beam campaigns



VMM3a hybrid for 128ch readout



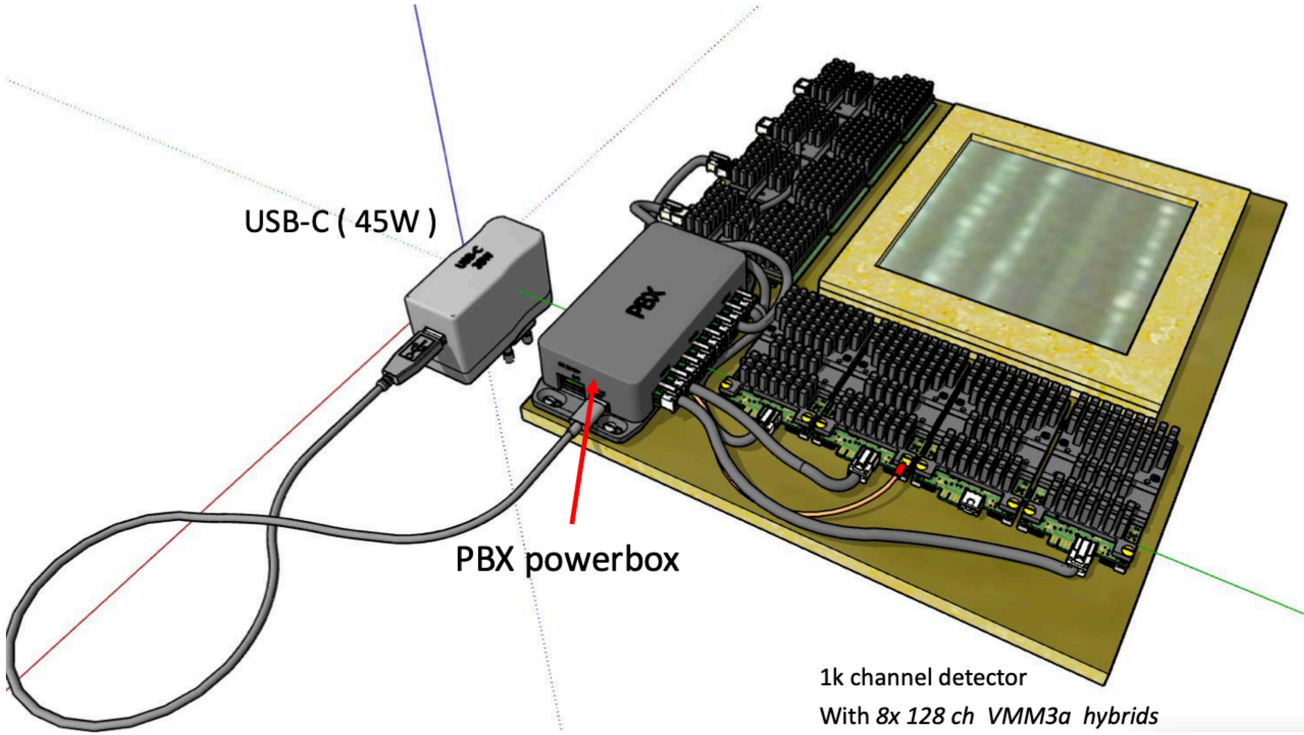
Hans Muller, https://indico.cern.ch/event/1360282/contributions/5786568/attachments/2790914/4867304/Scalable Readout System for DRD1.pdf
Hans Muller, https://indico.cern.ch/event/1632132/contributions/6960227/

PBX: Powerbox for powering front end hybrids

PBX Powerbox allows for low-noise powering of front end ASICs

This enables distributed systems and independent powering without relying on limited power over Ethernet connections.

Implementation of the power box has significantly facilitated commissioning of new systems due to simplified grounding and powering



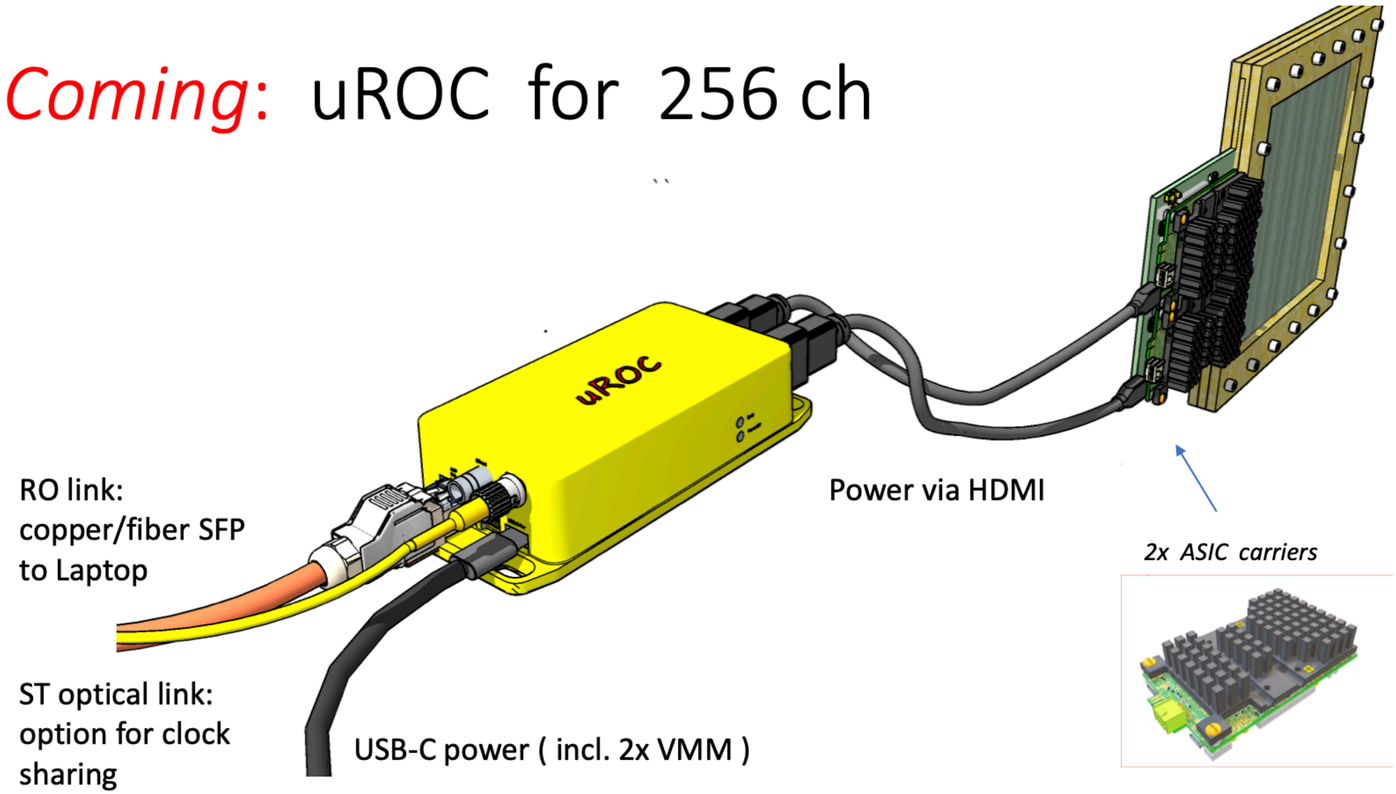
Hans Muller, https://indico.cern.ch/event/1360282/contributions/5786568/attachments/2790914/4867304/Scalable Readout System for DRD1.pdf
Hans Muller, https://indico.cern.ch/event/1632132/contributions/6960227/

µROC for small systems

Simplifying the testing of small detectors, µROC will enable the connection of two hybrids with 256ch in total

Ideally for prototype testing and low channel count systems

As a next step, maxiROC can be adapted for medium-sized detectors



Hans Muller, https://indico.cern.ch/event/1360282/contributions/5786568/attachments/2790914/4867304/Scalable Readout System for DRD1.pdf
Hans Muller, https://indico.cern.ch/event/1632132/contributions/6960227/

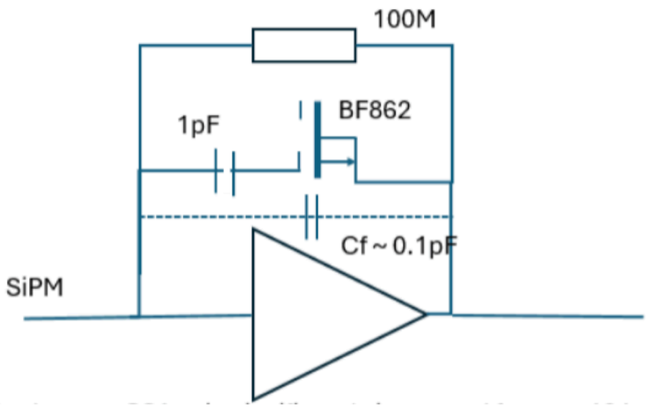
Analog front-end for gas detectors

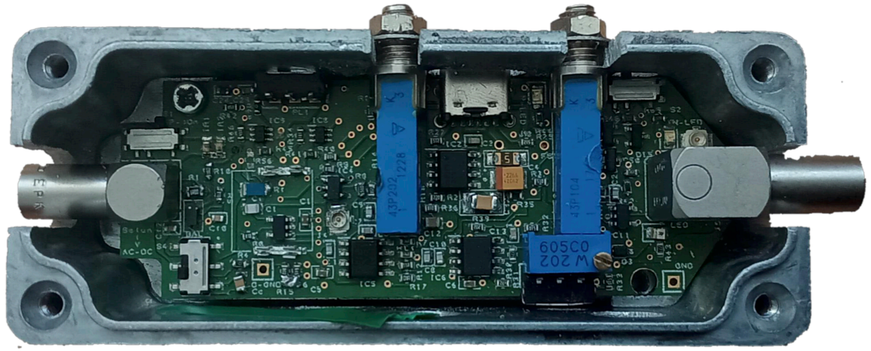
Study, characterization, implementation of new ideas on custom prototype amplifiers built with discrete components

Project goals:
- **Increase the dynamic range**; Using amplifiers with non linear characteristics
- **Increase the possible event rate**

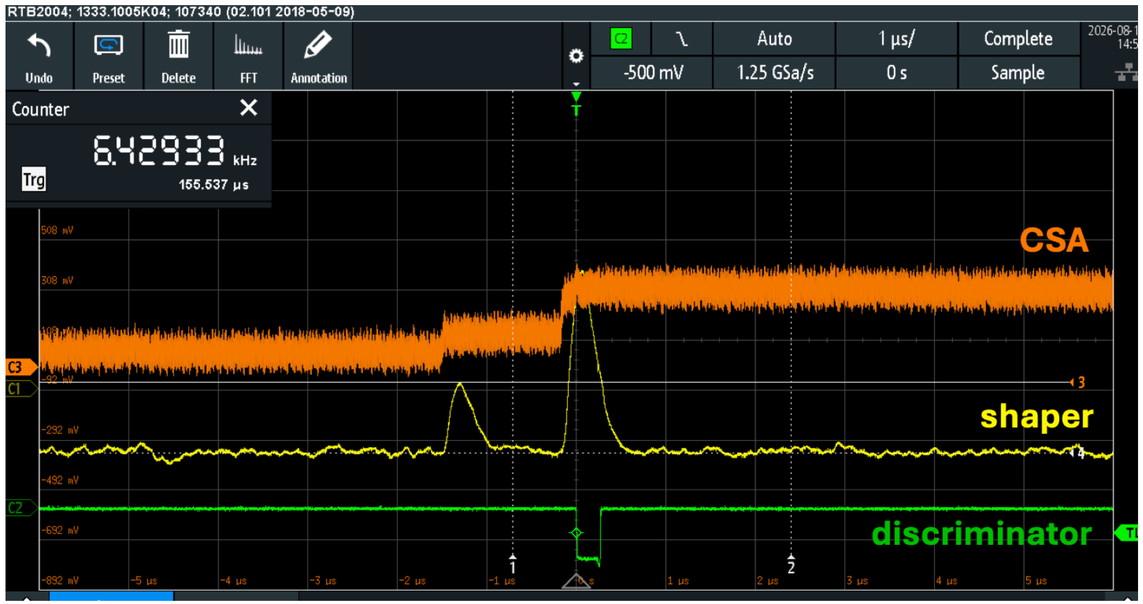
By making the amplifier discharge faster

Fast discharge with J-FET?





Custom board developed by Hans



Alessandro Cazacu: Summer student project under supervision of Hans Muller

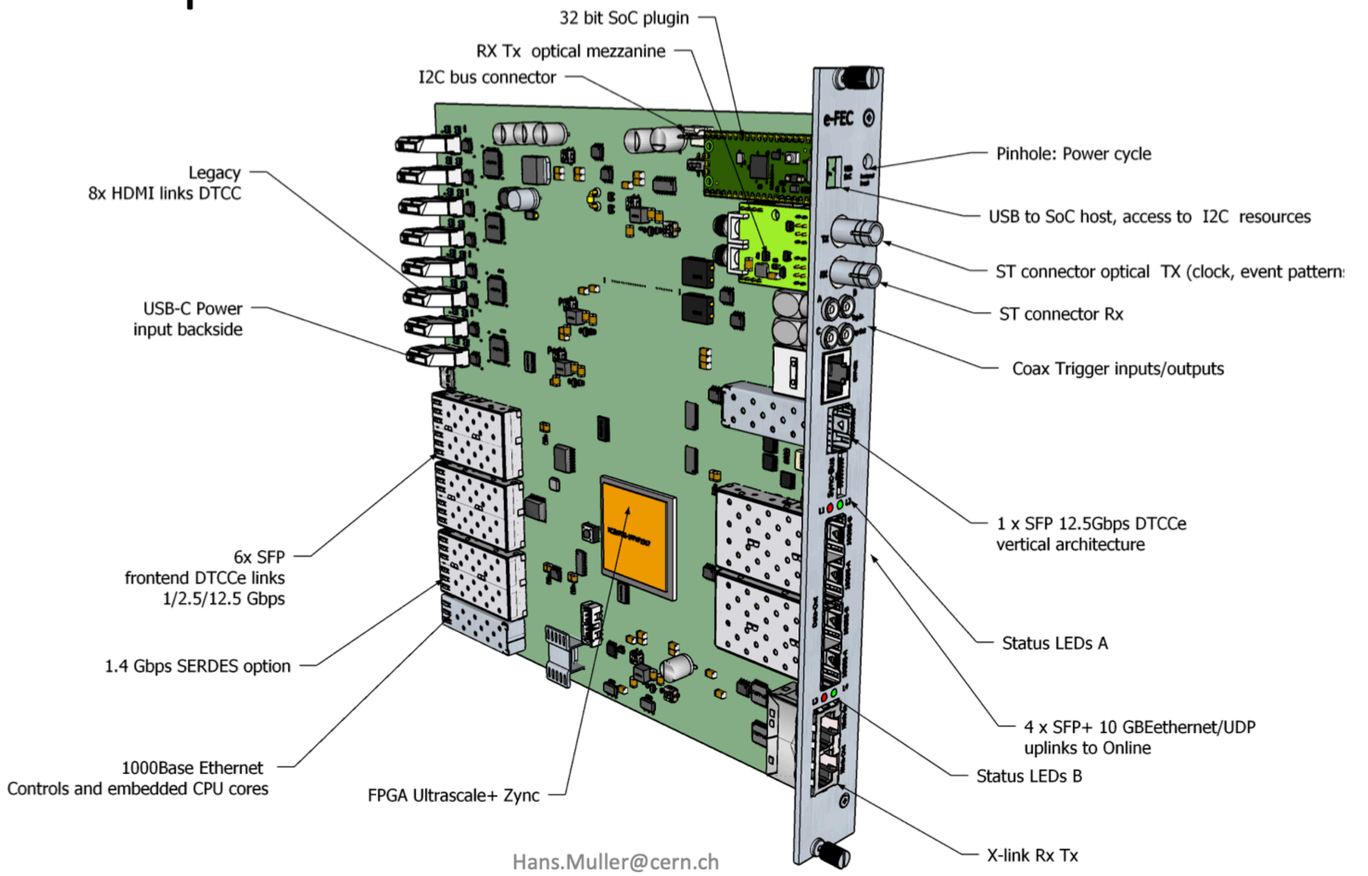
Next generation SRS: eFEC

Same physical outlines as FEC + DVMM together 6U x 220mm
• housed and powered (USB-C) in classic SRS crates
• Ultrascale+ Zync FPGA

• 8 x legacy, powered HDMI link ports to VMM frontend
• 6x frontend DTCCe link port SFP+ 1 / 2.5/ 12.5 Gbps
• 1x 100Base Ethernet for Controls link
• USB-C power connector

New possibilities: online triggers in FPGAs

eFEC card preview

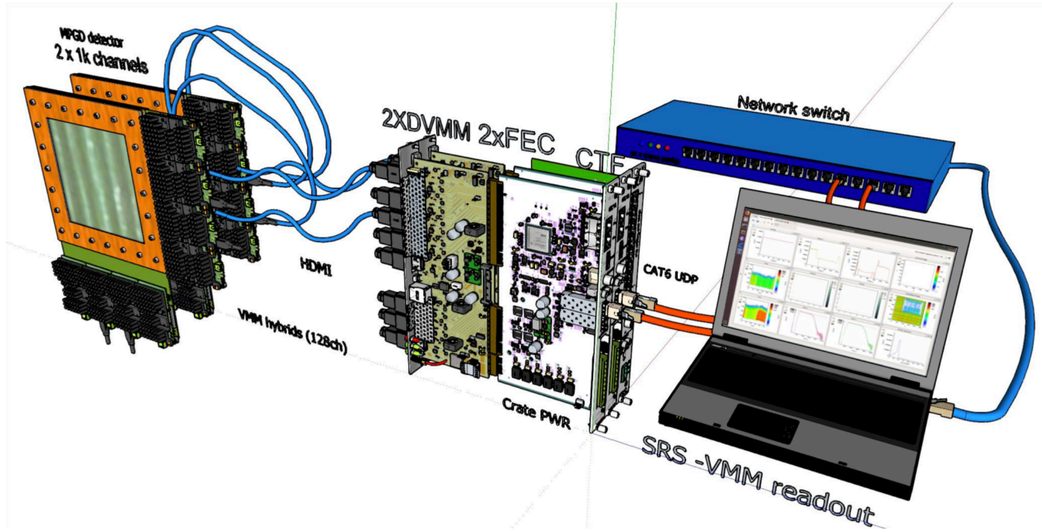


Hans Muller, https://indico.cern.ch/event/1360282/contributions/5786568/attachments/2790914/4867304/Scalable Readout System for DRD1.pdf
Hans Muller, https://indico.cern.ch/event/1632132/contributions/6960227/

Readout Electronics for Gaseous Detectors

Current status

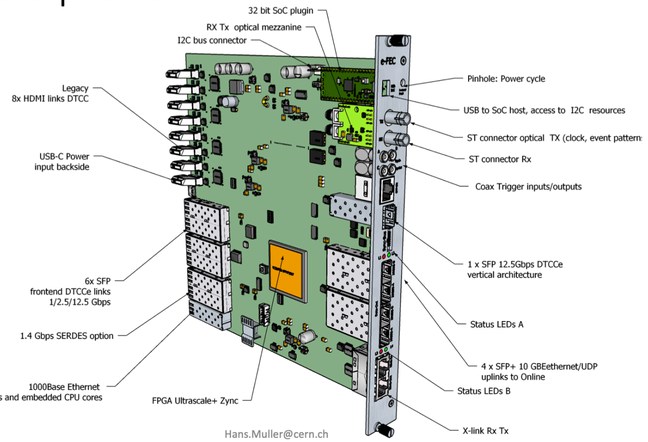
- **Versatile Scalable Readout System** developed in synergy with DRD1 collaboration WG5 (Electronics)
- Different front-end ASICs implemented in SRS
- Operation of **high-rate readout for beam telescopes** based on GEMs and Micromegas
- **Supporting electronics** including power-box, signal injector and translator electronics and universal preamplifiers



Next steps

- Development of **next-generation of SRS hardware** with DRD1 collaborators
- Evaluation of readout circuits including logarithmic preamplifiers

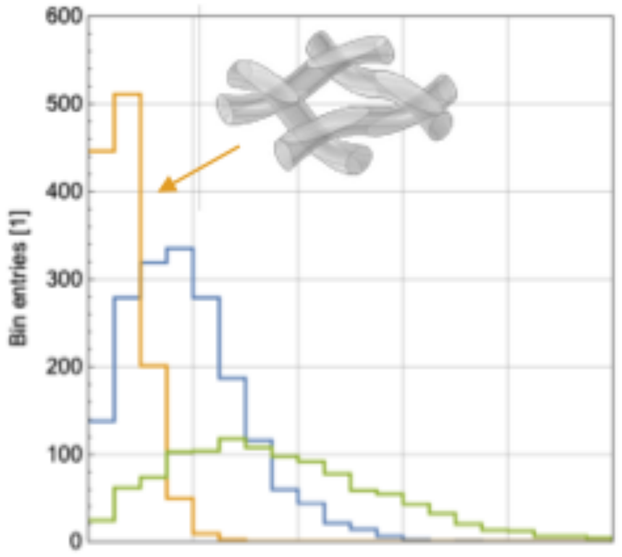
eFEC card preview

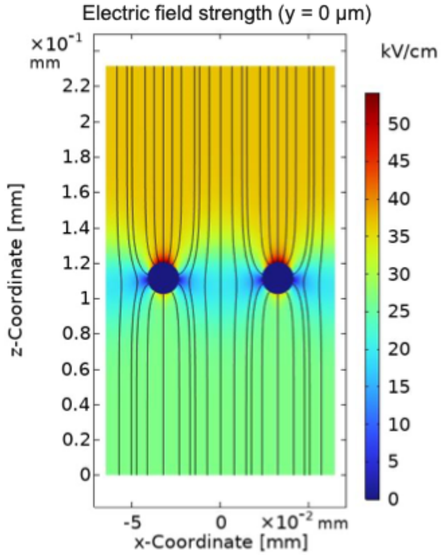


Modeling and Simulation

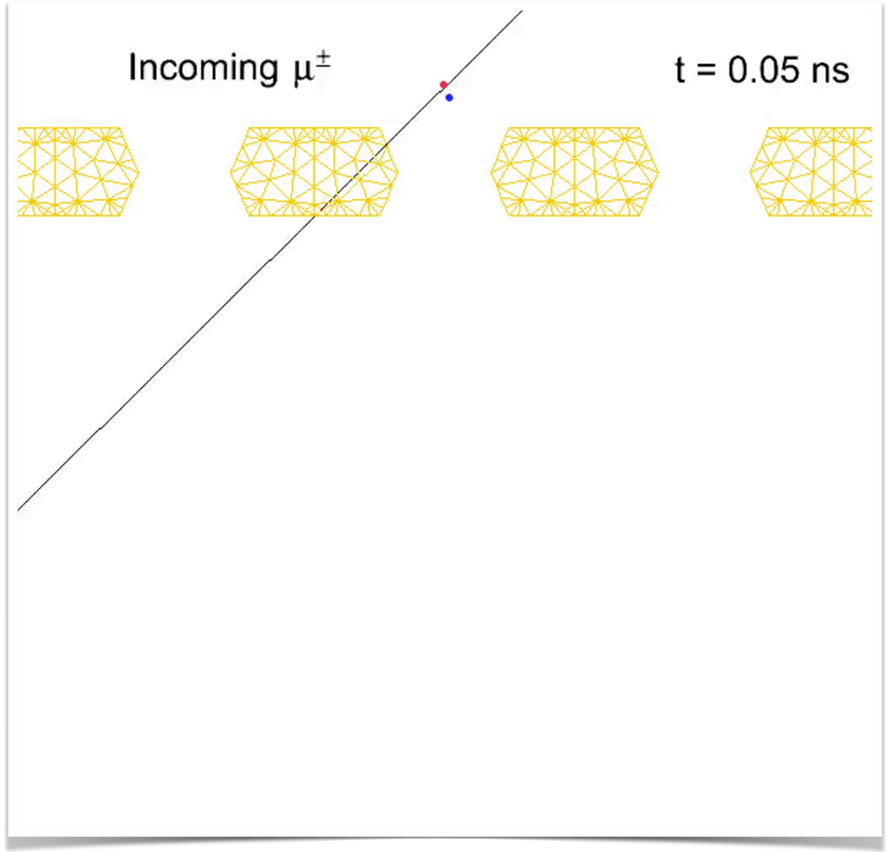
Simulation techniques

Garfield++ is an open-source Monte Carlo toolkit developed for **detailed simulations of particle detectors**, utilizing ionization measurements in both gases and semiconductors.





Avalanches in Gaseous Electron Multiplier (GEM)



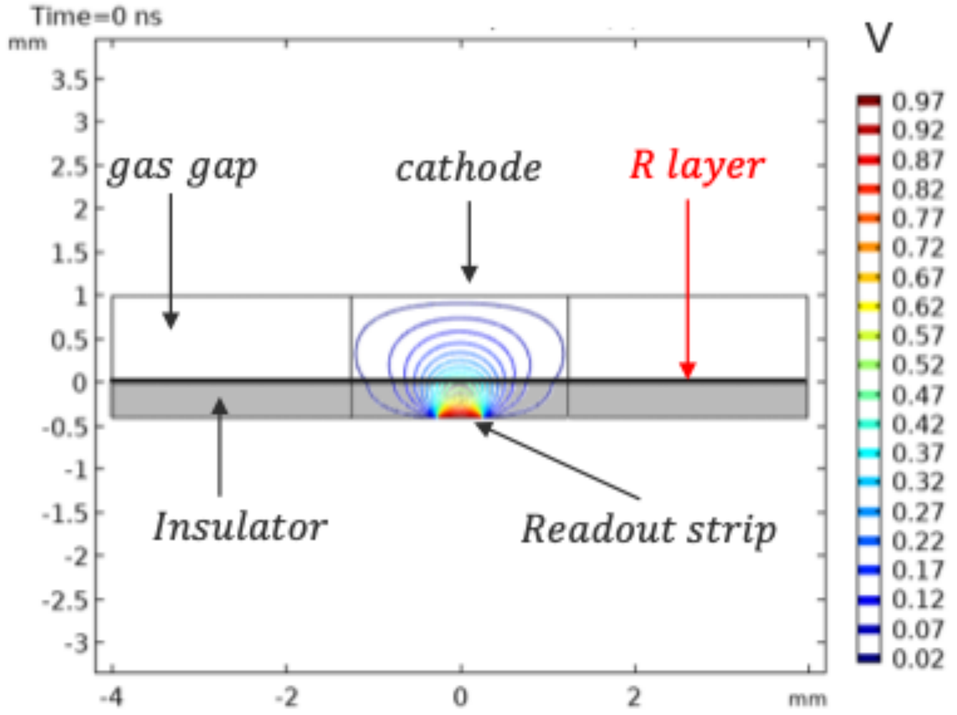
http://garfieldpp.web.cern.ch/garfieldpp/examples/gemgain/

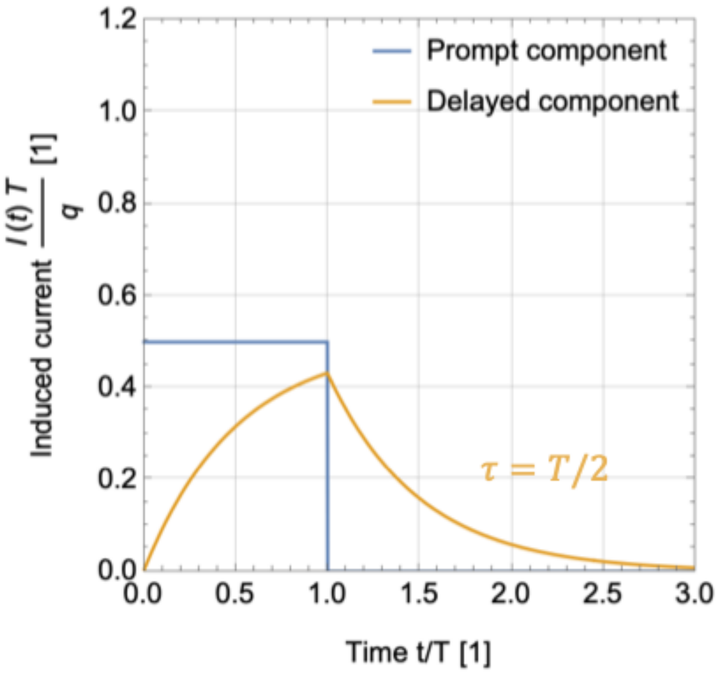
Djunes Janssens, EP R&D Seminar 2026 https://indico.cern.ch/event/1654154/contributions/6953732/attachments/3247780/5796285/EPR&D@2026_WP2.pdf

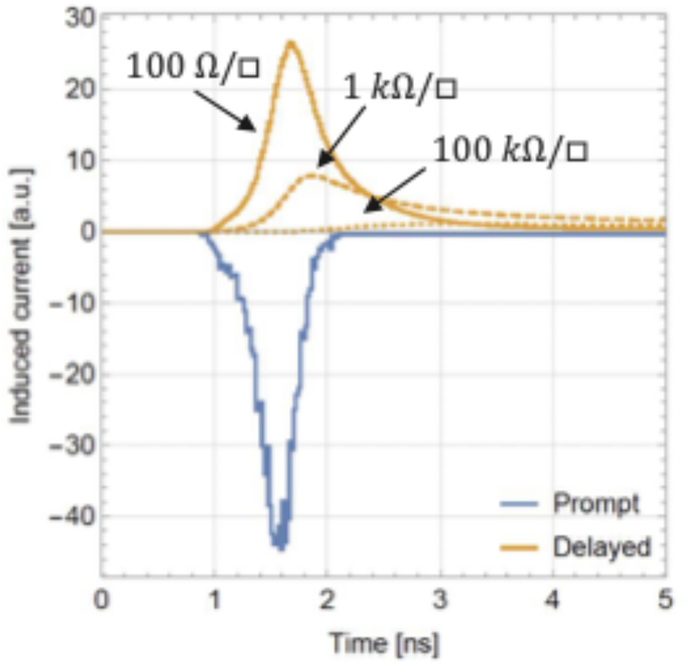
Ramo-Shockley theorem extension for conducting media

For detectors with resistive elements, the **time dependence** of the signals is not solely given by the **movement of the charges** in the drift medium but also by the **time-dependent reaction of the resistive materials**.

Calculation of **prompt and delayed signal components** in conducting media allows simulation of detectors with resistive electrodes.



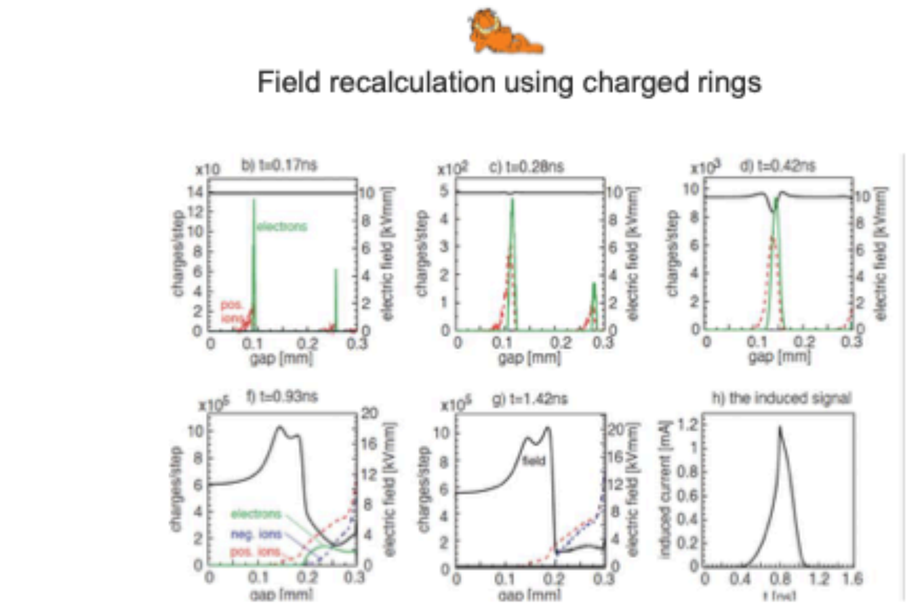


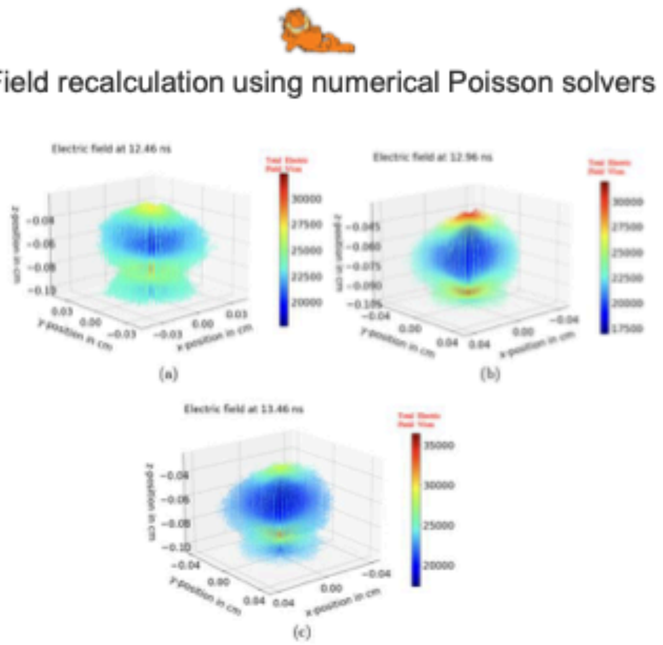


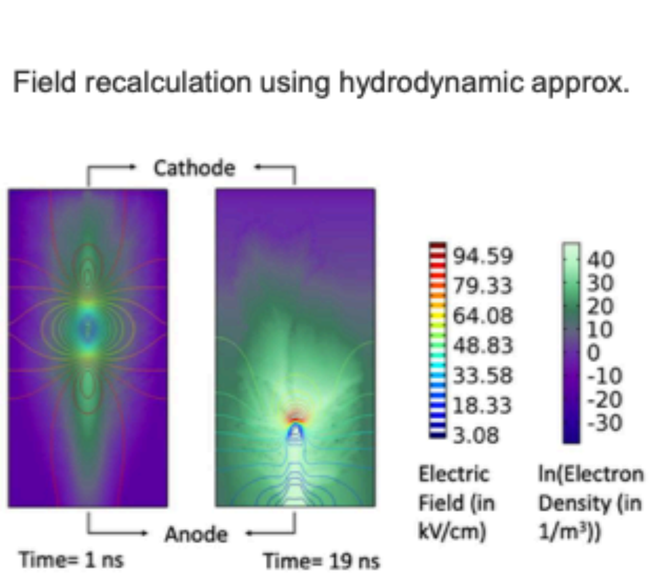
Djunes Janssens, EP-DT Training Seminar, https://indico.cern.ch/event/1339732/attachments/2744111/4774312/DTSeminar2023DjunesJanssens.pdf

Space-charge Calculations Methods Under Development in DRD1

For the simulation of gaseous detectors, different approaches are being developed to include the **interplay between avalanche development and space-charge field modifications**. Two distinct approaches are under development in Garfield++:





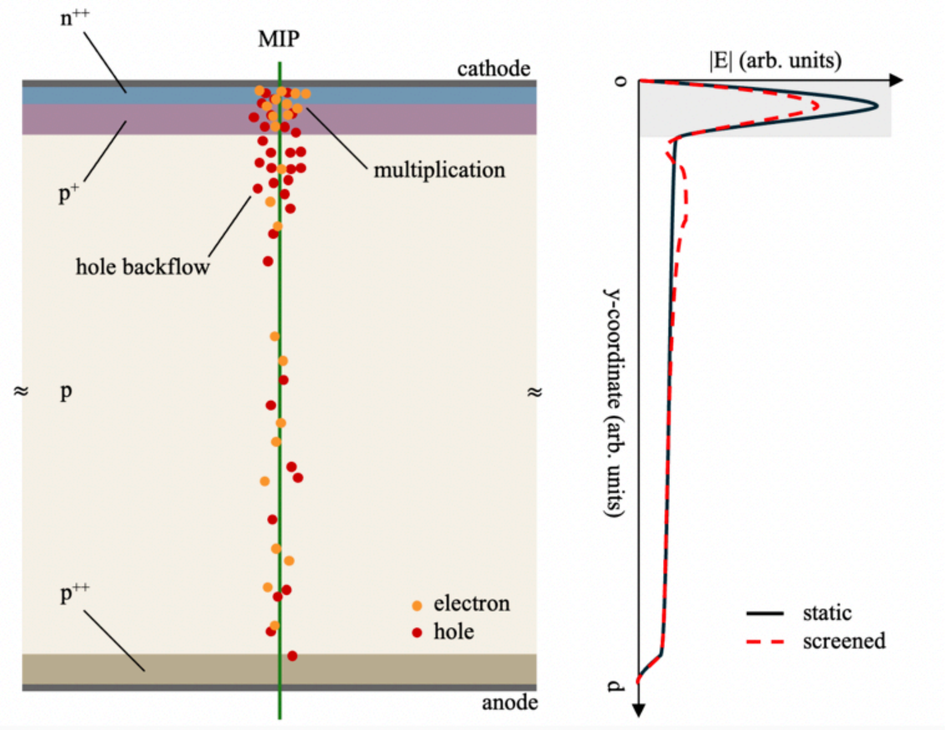


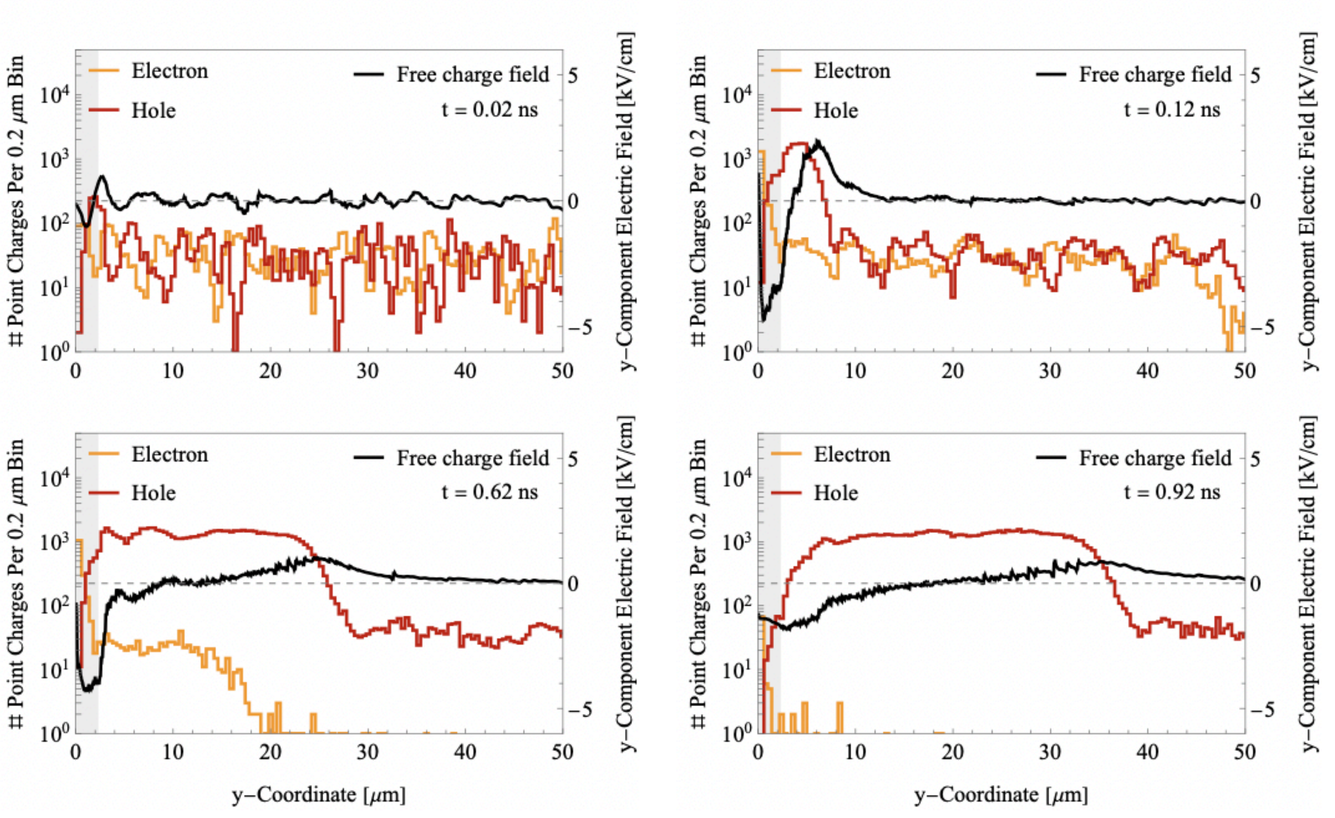
Space-charge field = field from the free charge carrier densities

Djunes Janssens, EP R&D Seminar 2026 https://indico.cern.ch/event/1654154/contributions/6953732/attachments/3247780/5796285/EPR&D@2026_WP2.pdf

Space-charge gain suppression in LGADs

Garfield++ Monte Carlo with the free-carrier field superimposed on the TCAD field showed that the avalanche screens the gain layer event by event, compressing the Landau tail and improving the time resolution of a 50 µm LGAD from 53.9 ps to 44.5 ps.

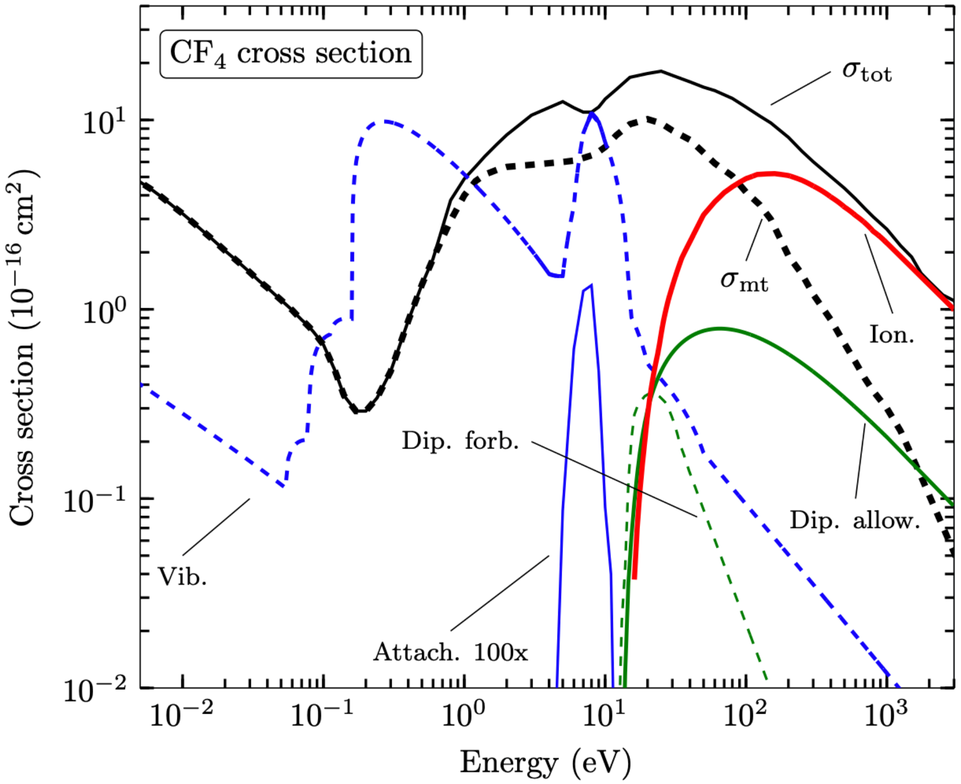


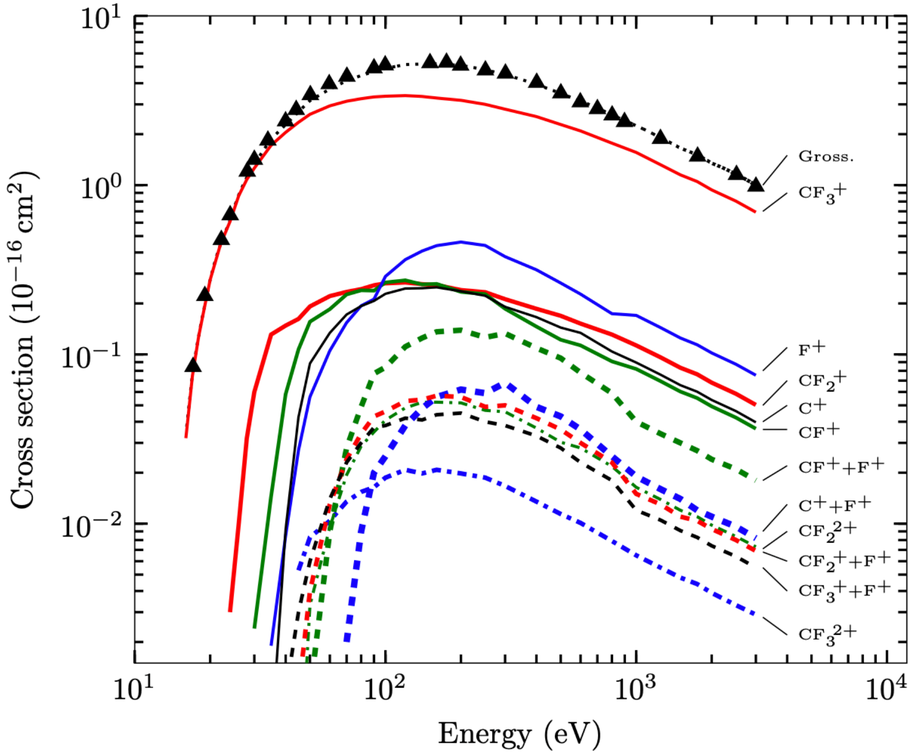


D. Janssens, M. Moll, H. Schindler, arXiv:2609.08666 https://arxiv.org/abs/2609.08666

Porting Magboltz to C++

The electron-molecule scattering cross sections implemented in magboltz for tetrafluoride CF4 are used to benchmark magboltz++, which is a **newly presented C++ version of magboltz**.



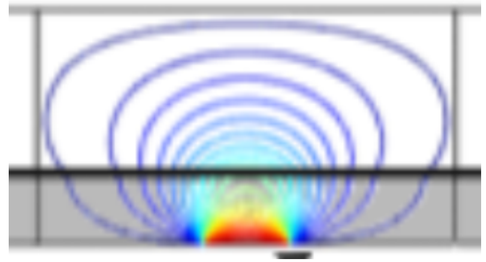


Marnik Metting van Rijn and H. Schindler

Modeling and Simulation

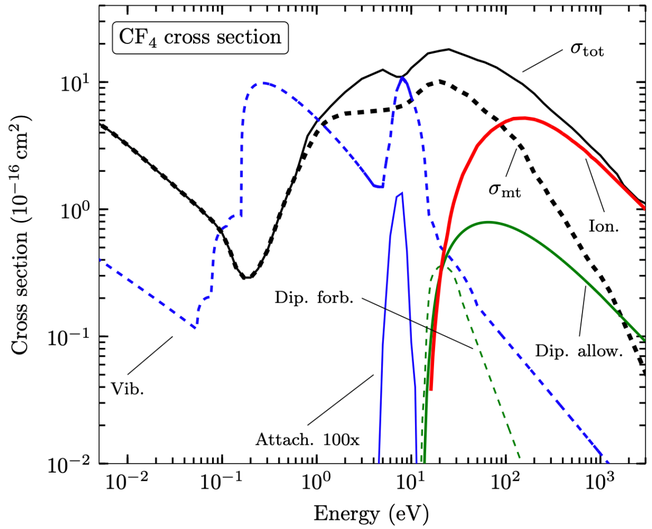
Current status

- **Modelling of MPGD structures** in close collaboration with **DRD1 WG4 (Simulation)**
- Extension of Garfield++ and modelling framework for **resistive elements**
- Modelling of **delayed and prompt signals**
- Simulation-driven design of novel detector structures including PICOSEC Micromegas



Next steps

- Techniques to **model large avalanches** and performance optimisation in synergy with DRD1 collaborators
- **Implementation of space-charge effects** and modelling of high-gain operation
- Simulation-driven exploration of alternative gases including environmentally-friendly options
- **Porting of Magboltz to C++** and validation with well-known gases

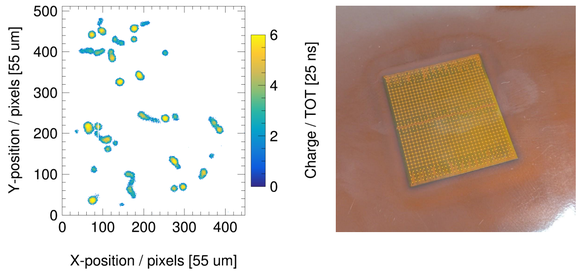


MPGD developments at CERN's Gaseous Detector Development laboratory

Pixellated readout

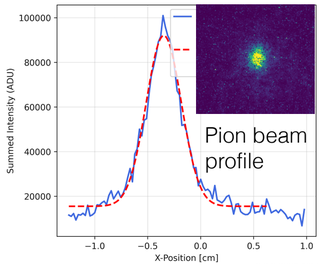
Charge readout

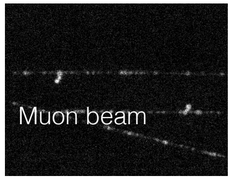
- Integration of Timepix4 with gaseous amplification stages
- Manufacturing tests towards hybrid detectors with embedded TSV Timepix 4 and μRWELL conducted at MPT workshop



Optical readout

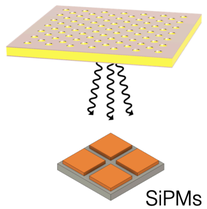
- Event-by-event particle tracking and integrated beam profile measurement of muon and pion beams in SPS H4
- Evaluation of high-speed CMOS camera for real-time beam profiling

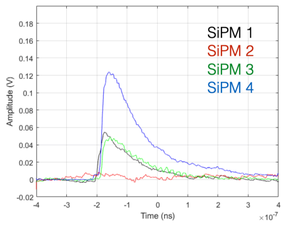




SiPM readout

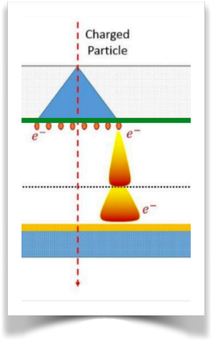
- Secondary scintillation light readout with SiPMs
- mm-scale spatial resolution and down to <150ps timing resolution achieved (Optical PICOSEC)

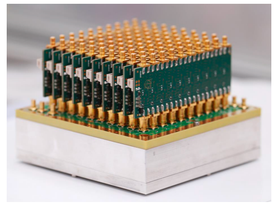




Precise timing detectors

- Down to <15ps timing resolution achieved with single-channel PICOSEC Micromegas prototypes
- Tileable 10x10 channel modules
- Performant UV photocathodes with improved robustness

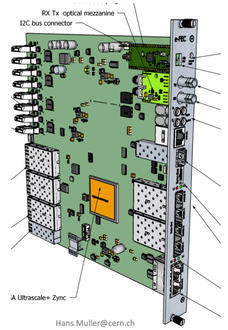




Readout electronics

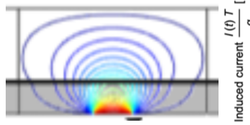
- Development of next generation of Scalable Readout System
- Modular readout system components including μROC
- Support electronics including power box, signal injectors, etc.

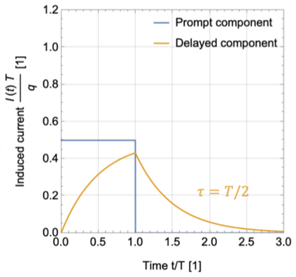




Modeling and simulation

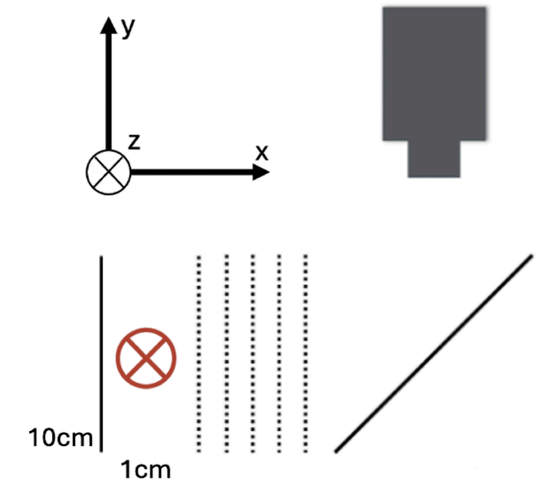
- Extension of simulation tools to handle resistive elements including prompt and delayed signal components
- Performance optimisations including techniques to simulate large avalanches and space charge



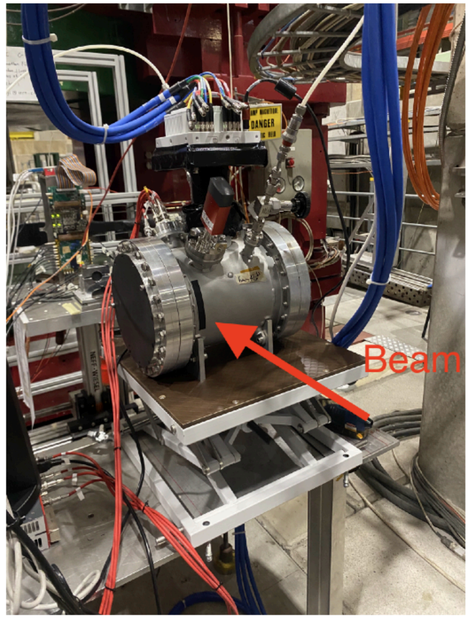


Backup

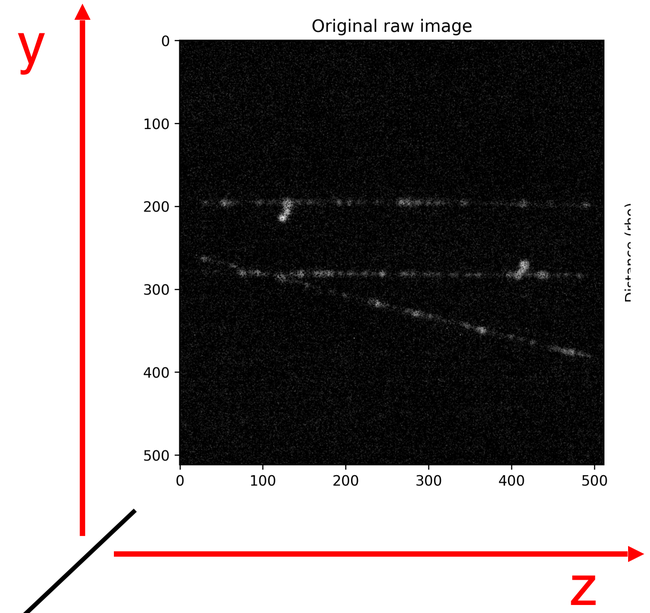
Track reconstruction with Hough transform

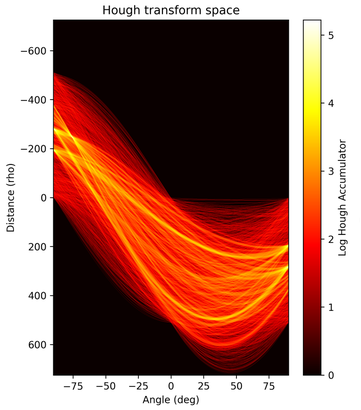


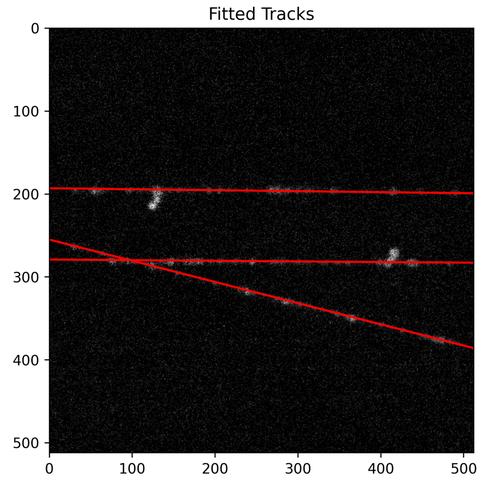
not to scale



Projection in z-y plane (vertical)



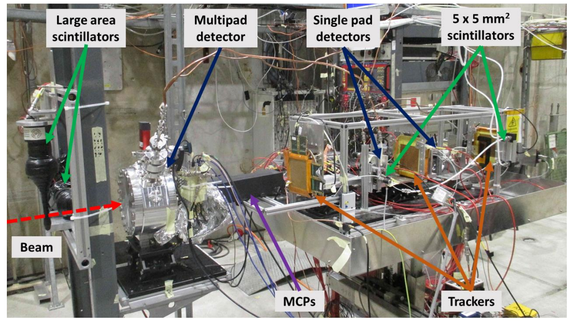




Measurement of beam divergence:

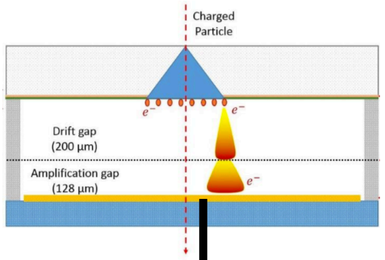
- Acquisition of muon trajectories and reconstruction of direction with Hough transform
- Visualise effect of divergence due to magnetic field

Timing resolution measurements



Induced signals are recorded from anode pads, amplified and digitised

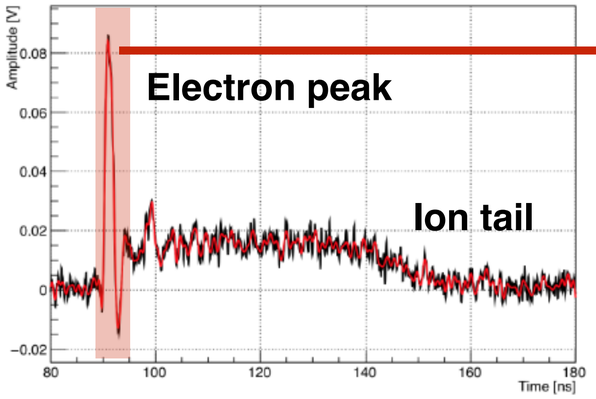
Rising edge of fast electron peak is used for timing measurements with CFD to account for time walk



Preamplification of induced signal

Digitized by high-bandwidth oscilloscope @ 20GSamples/s

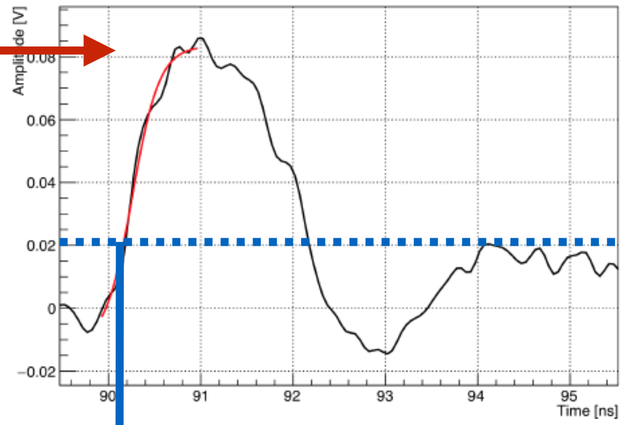
Recorded waveform



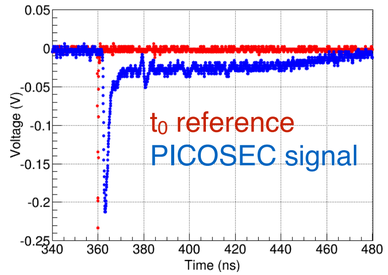
Signal with two distinct components:

- Electron peak: fast (≈0.5 ns)
- Ion tail: slow (≈100 ns)

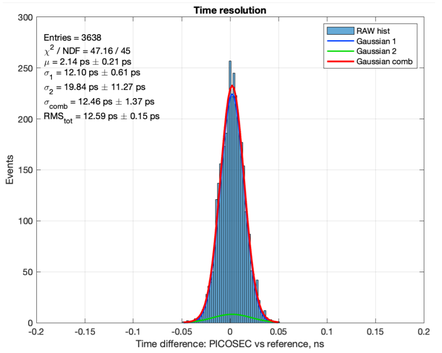
Zoom: electron peak



Constant Fraction Discrimination (**CFD**) at 20% on the fitted noise-subtracted e-peak



Time difference between signal and reference



<20 ps timing resolution (for MIPs)

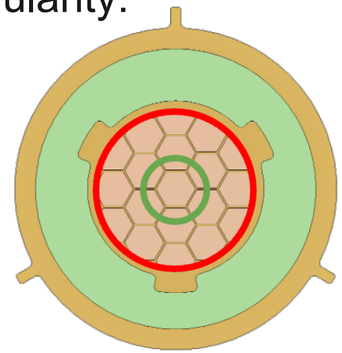
Schematic not drawn to scale

Preliminary

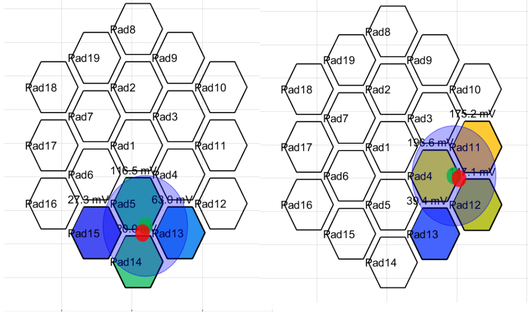
Increased readout granularity

For 3.5 mm readout pad pitch, comparable timing performance was observed on the central pad, despite only having partially contained events, with most charge centered around the particle trajectory.

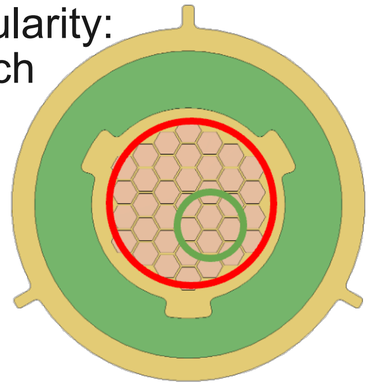
Medium granularity:
3.5mm pitch



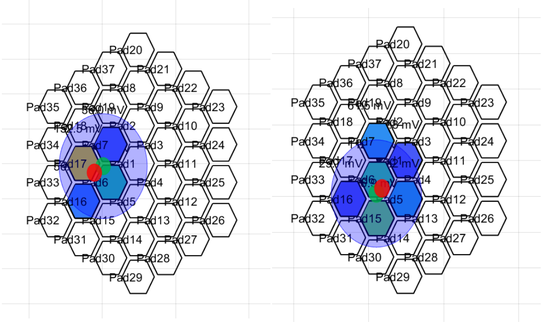
Example muon events

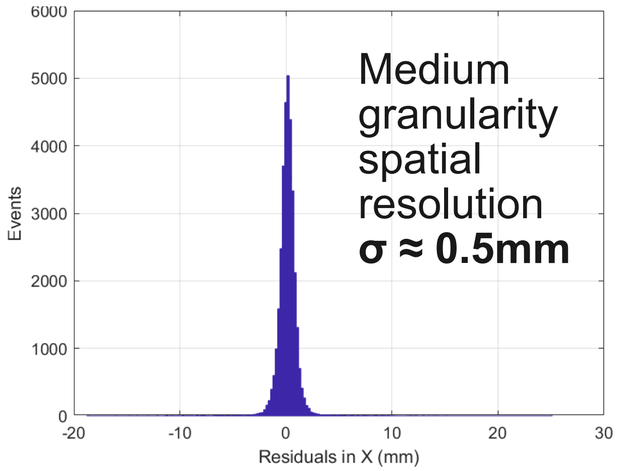


High granularity:
2.2mm pitch



Example muon events





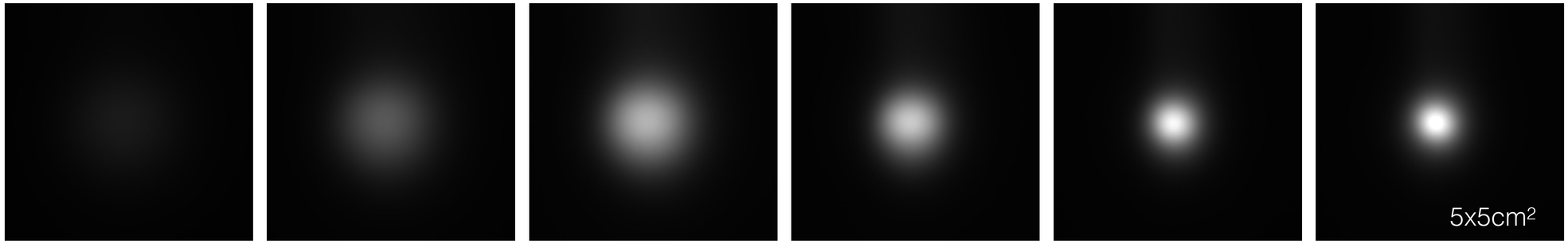
Schematic not drawn to scale

	single pad	medium granularity	high granularity
pad pitch [mm]	15.0	3.5	2.2
mean signal ampl. [mV]	193	157.8	62.3
central pad σ_t [ps]	13.9	16.9 ± 0.15	28.3 ± 0.3
cluster size	1	4.0	3.6
x-residuals (full active area) [mm]	/	1.04	1.03
x-residuals (inner 6mm circle) [mm]	/	0.5	0.65

Both timing and spatial resolution are worse for the high granularity readout, most likely due to the smaller signal amplitudes and imperfect pad connections.

Proton pencil beam profile

Recorded CCD images of centered single beam spots at different energies show decreasing beam spot width with increasing beam energy



60 MeV, 0.4nA	80 MeV, 1nA	100 MeV, 2nA	150 MeV, 2nA	200 MeV, 2nA	226 MeV, 2nA

Pixel intensity can be used to measure 2D distribution of deposited energy

Scanning beam energy and current, profile images from highest possible current

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

Need of CF_4-based gas mixtures
or wavelength shifters

Phantom S710

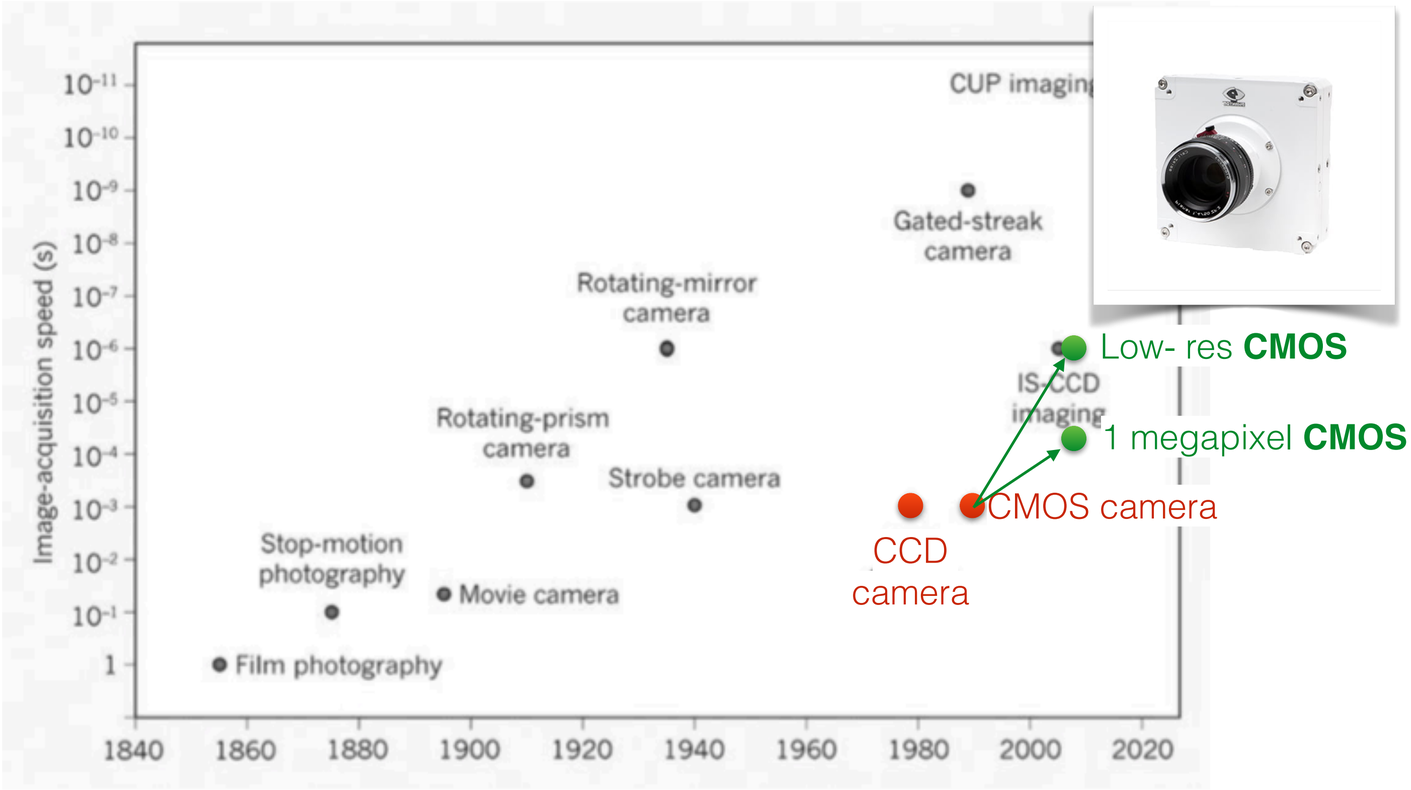


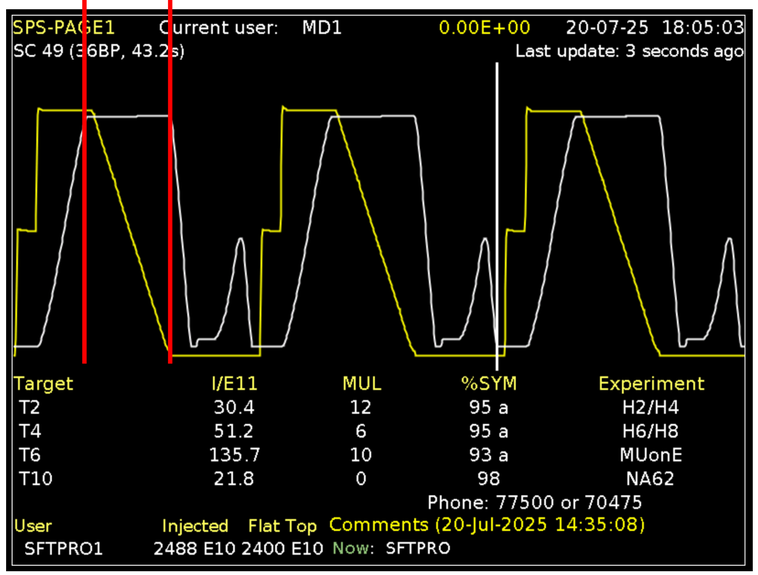
Image adapted from: B. Pogue, Nature 516 (2014) 46–47

DRD1 SPS H4 test beam campaign 2025

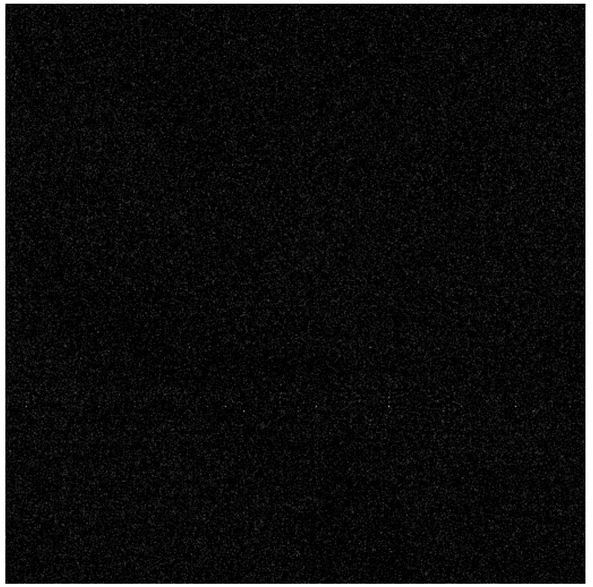
Test of acquisition and reconstruction software in beam conditions

- Accurate reconstruction of particle counts per spill and agreement of event-by-event vs. integrated beam profiles.
- Investigating spatial beam profile development during spills (+ beam divergence and temporal profiles)

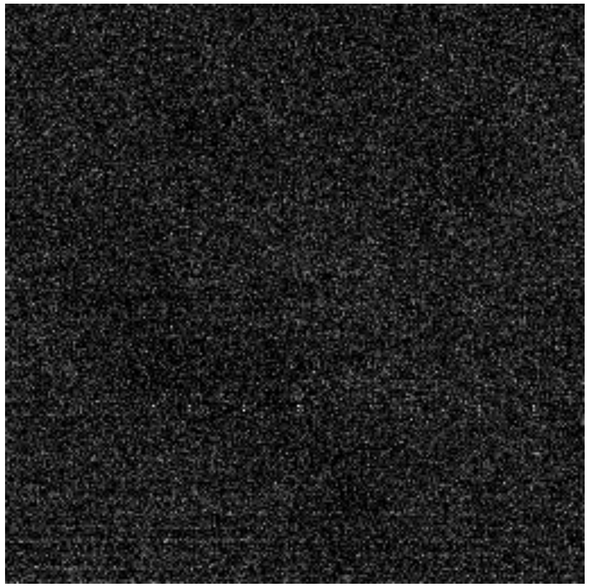
4-5s of spill



Muon Beam Spill (5s)
30Hz, 30ms



Pion Beam Spill (5s)
30Hz, 3ms



WP2 - Gaseous Detectors - Highlights 2025

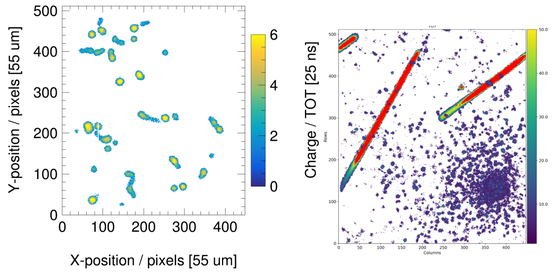
Pixellated readout

Charge readout

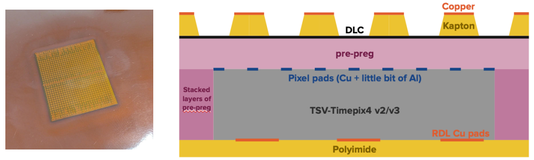
- Integration of Timepix4 with gaseous amplification stages (triple GEM, µRWELL)
- Simulation of signal coupling to pixellated readout chip
- Low energy photoelectron track detection in He gas mixture
- Manufacturing tests towards hybrid detectors with embedded TSV Timepix 4 and µRWELL conducted at MPT workshop

X-ray imaging

GEMPix4



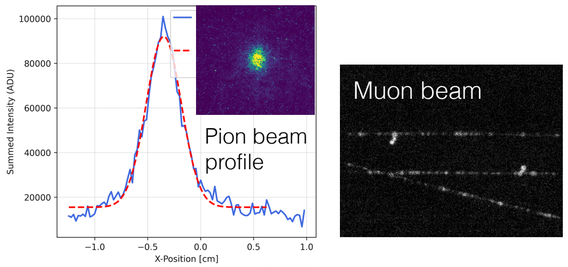
Low-energy photoelectrons in He mixture, alpha tracks



Encapsulation test of Timepix4 for µRWELL integration

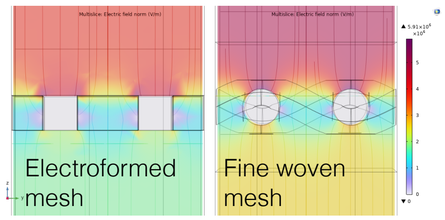
Optical readout

- Event-by-event particle tracking and integrated beam profile measurement of muon and pion beams in SPS H4
- Evaluation of high-speed CMOS camera for real-time beam profiling

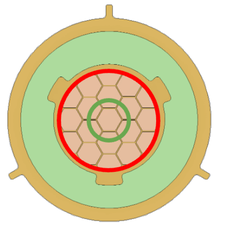


Precise timing detectors

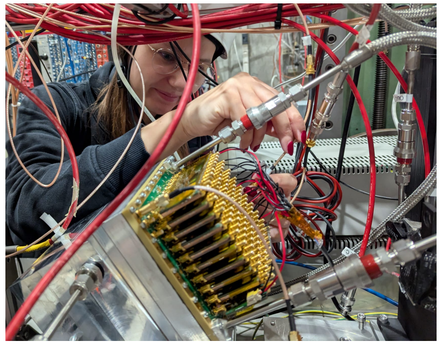
- Optimisation of timing resolution of tile-able multi-channel prototypes
- Evaluation of high readout granularity for improved spatial resolution
- Implementation and characterisation of double DLC layers for vertical charge evacuation in high-rate Micromegas layout
- Deposition and evaluation of carbon-based and metallic photocathodes at MPT and TFG workshops (thin Ti, B4C, DLC)
- Adaptation of 10cm x 10cm prototype for UV photon detection and beam tests with Cherenkov radiators
- Simulation of impact of mesh geometry on achievable gain and timing resolution and production of new Micromegas with optimised choice of high-transparency woven mesh



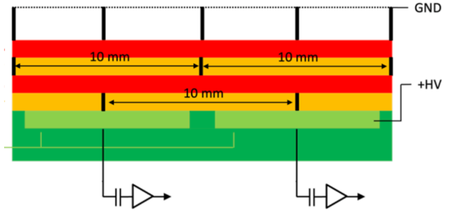
Simulation for mesh optimisation



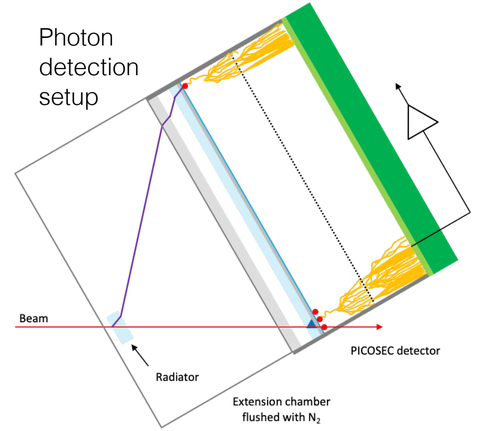
High readout granularity



Picosec module readout



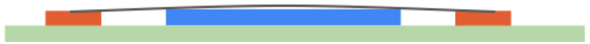
High-rate layout with vertical charge evacuation implemented with double DLC layers

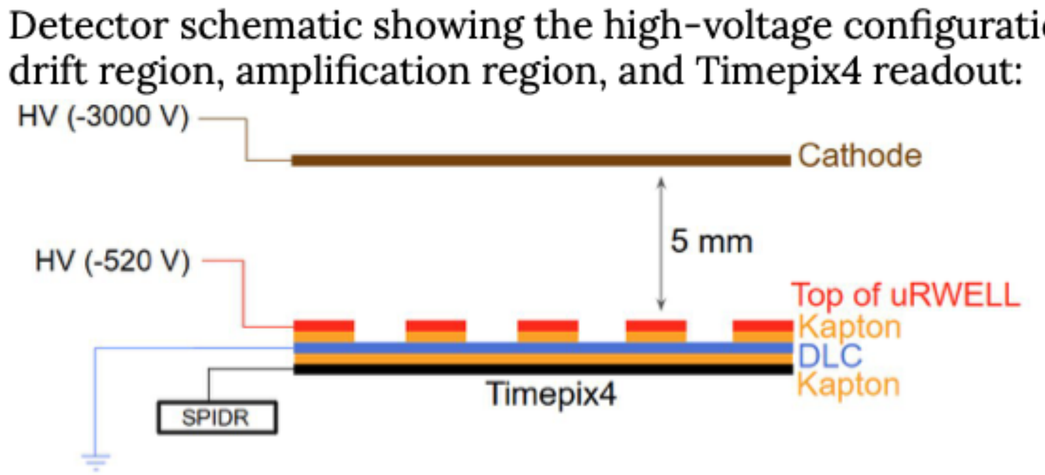


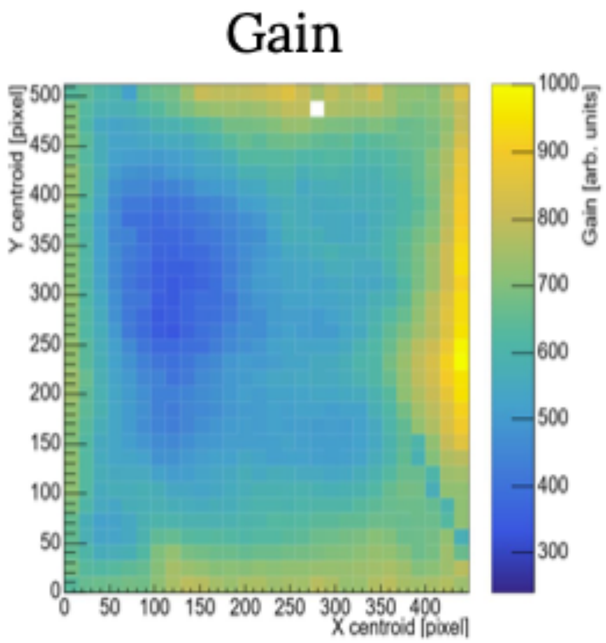
Coupling Timepix4 to μRWELL

Timepix4 mounted on PCB
μRWELL foil stretched and mounted on top

No direct integration but only mechanical coupling
(possibility of poor uniformity of coupling)







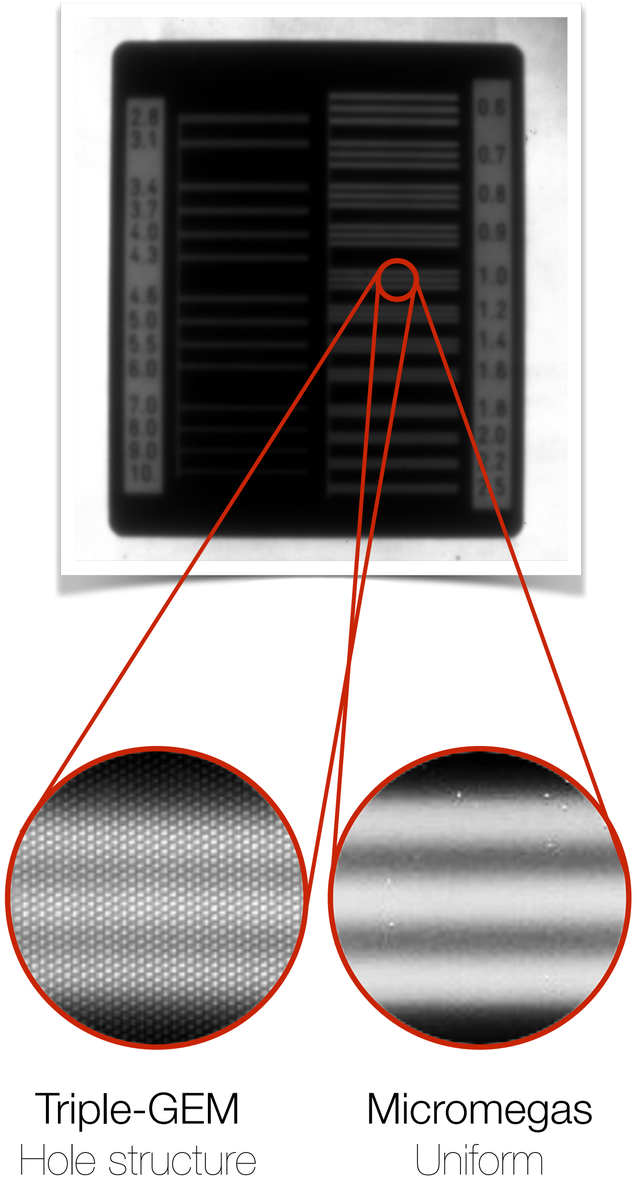
Eliska Jelinkova. David Marques, DRD1 Collaboration Meeting June 2026
https://indico.cern.ch/event/1662850/contributions/7133781/attachments/3304919/5913930/Coimbra (1).pdf

Optical readout

Beam monitoring has been realised with different MicroPattern Gaseous Detectors (MPGDs), most importantly with Gaseous Electron Multipliers (**GEMs**) and Glass **Micromegas**

- GEMs show characteristic **hole structure** in recorded images
- Micromegas exhibit more **uniform response** and better spatial resolution

- **GEMs** allow for **higher amplification** factors in multi-GEM cascades at the expense of increased blurring (transverse diffusion)



Triple-GEM
Hole structure

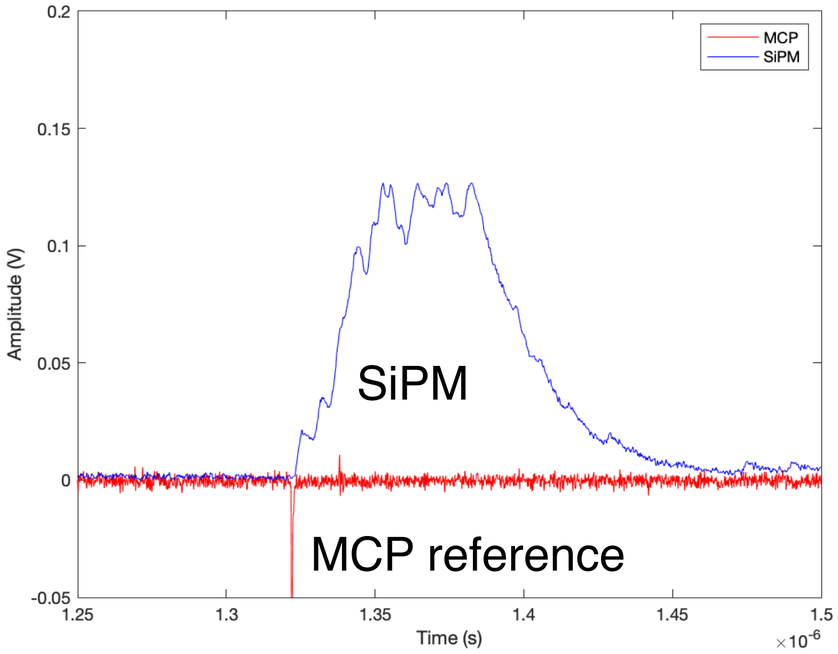
Micromegas
Uniform

SiPM signals

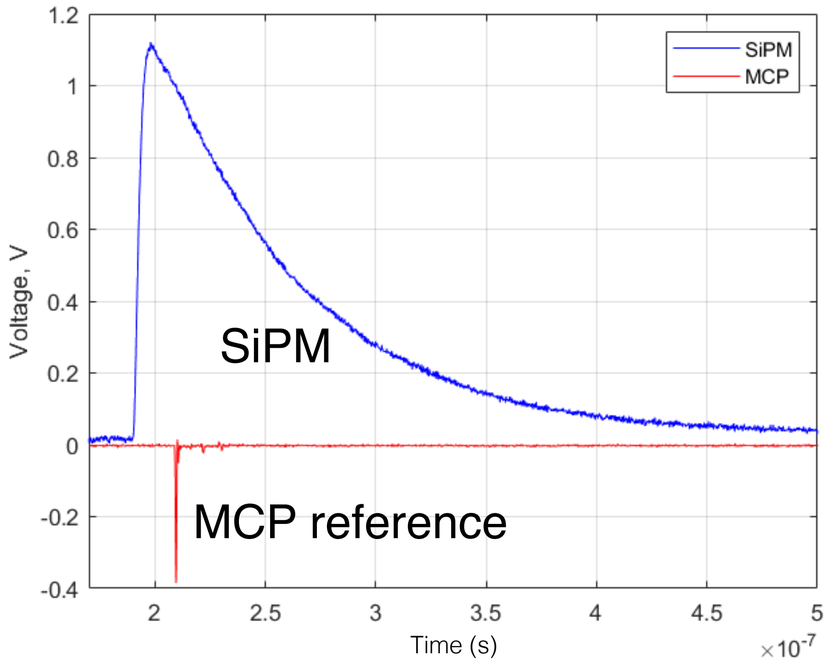
For low gain on Micromegas, arrival of individual photons is visible

For higher gain, waveforms are smoother and show envelope of arrival of many photons

Low optical gain in Ar/CF4 - individual photons visible



High optical gain in Ne/CF4/Ethane with TPB wavelength shifter



Photocathode characterisation

Ageing studies

- **Timing measurements after each ageing step**:

  → fresh

  → air exposure

  → UV irradiation

  → charge accumulation

- Measurement details:

  - all materials were aged stepwise on the same sample, except CsI, for which each step used a separate one
  - data points for each material were measured at the highest common V_C across ageing steps: 480 V for most materials, 445 V for CsI, and 490 V for DLC
  - Ti, B_4C, and DLC were stored in air (no “fresh” data point), while the other materials under vacuum
  - B_4C and DLC were unstable after current accumulation, likely due to no Ti layer, preventing final measurements

