# Muon beam characterization with a GridPix-TPC

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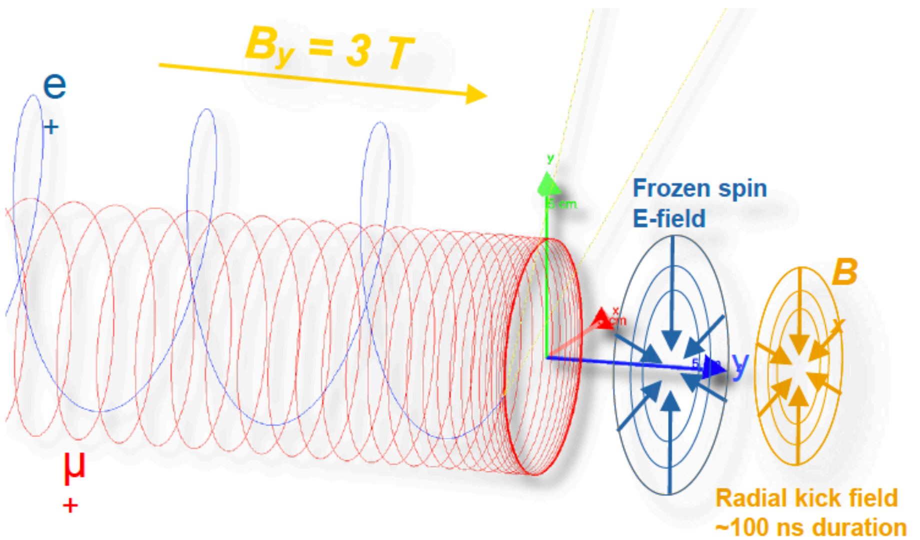
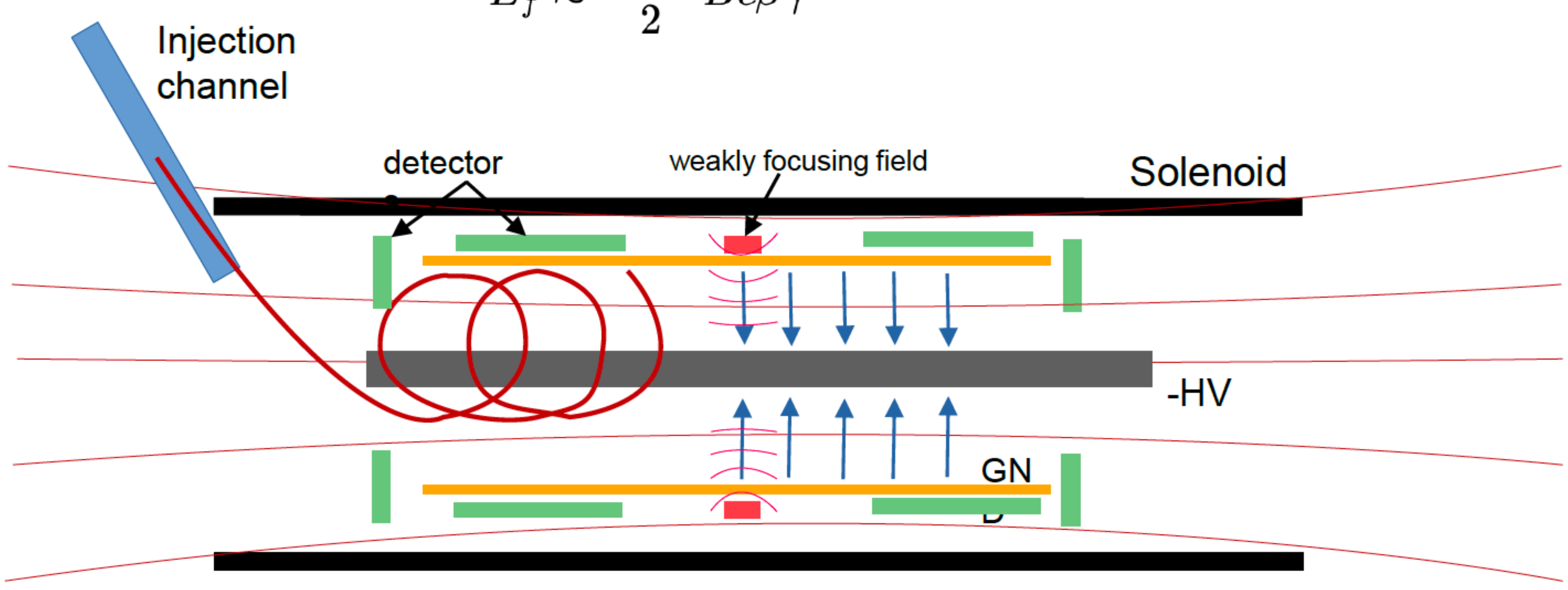
# The general experimental idea

- Muons enter the uniform magnetic field
- A radial magnetic field pulse stops them within a weakly focusing field where they are stored
- Radial electric field ‘freezes’ the spin, so that the precession due to the MDM is cancelled

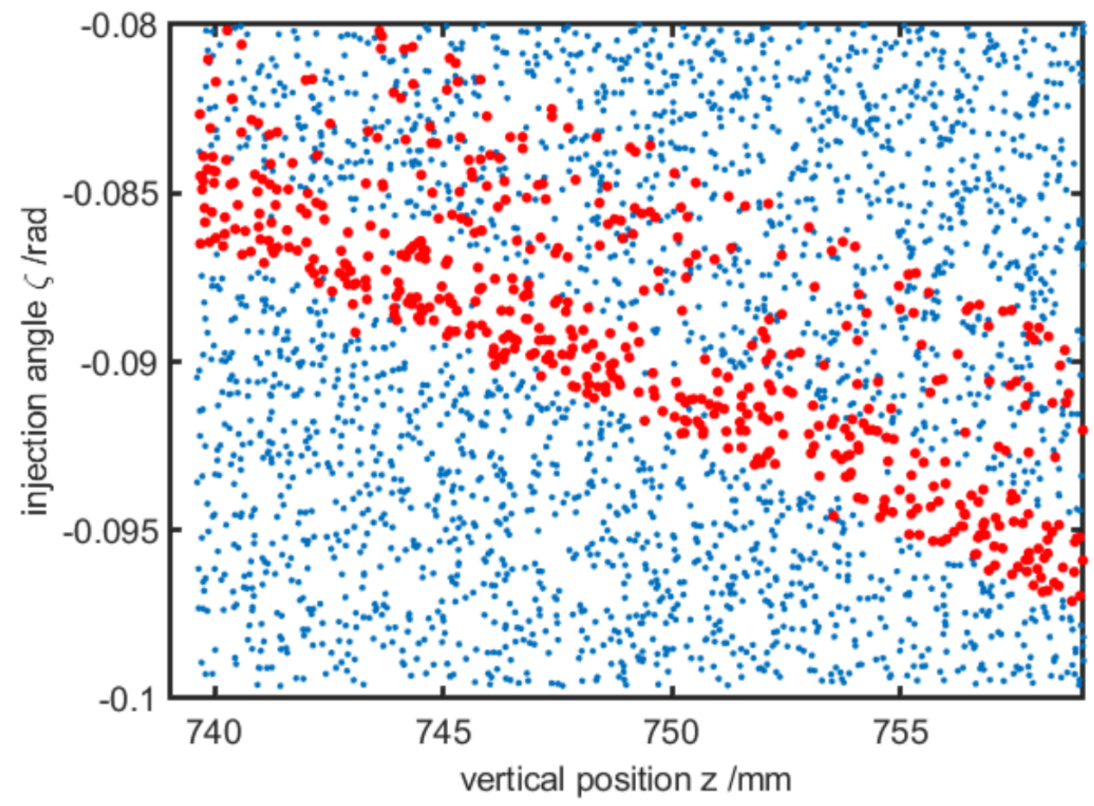



$$E_f \approx \frac{g-2}{2} B c \beta \gamma^2$$



# Storing efficiency

- Muons are stored only if they lie in a **very small region of the beam phase space**
  - ~ $5 \times 10^{-4}$ storage efficiency
- This region is selected by the injection channels, acting as collimators
  - channels misaligned by a few mrad x mm would preferentially select muons that cannot be stored
  - it is necessary to have detectors that can characterize the selected muon phase space when aligning the different components of the injection line to the magnet

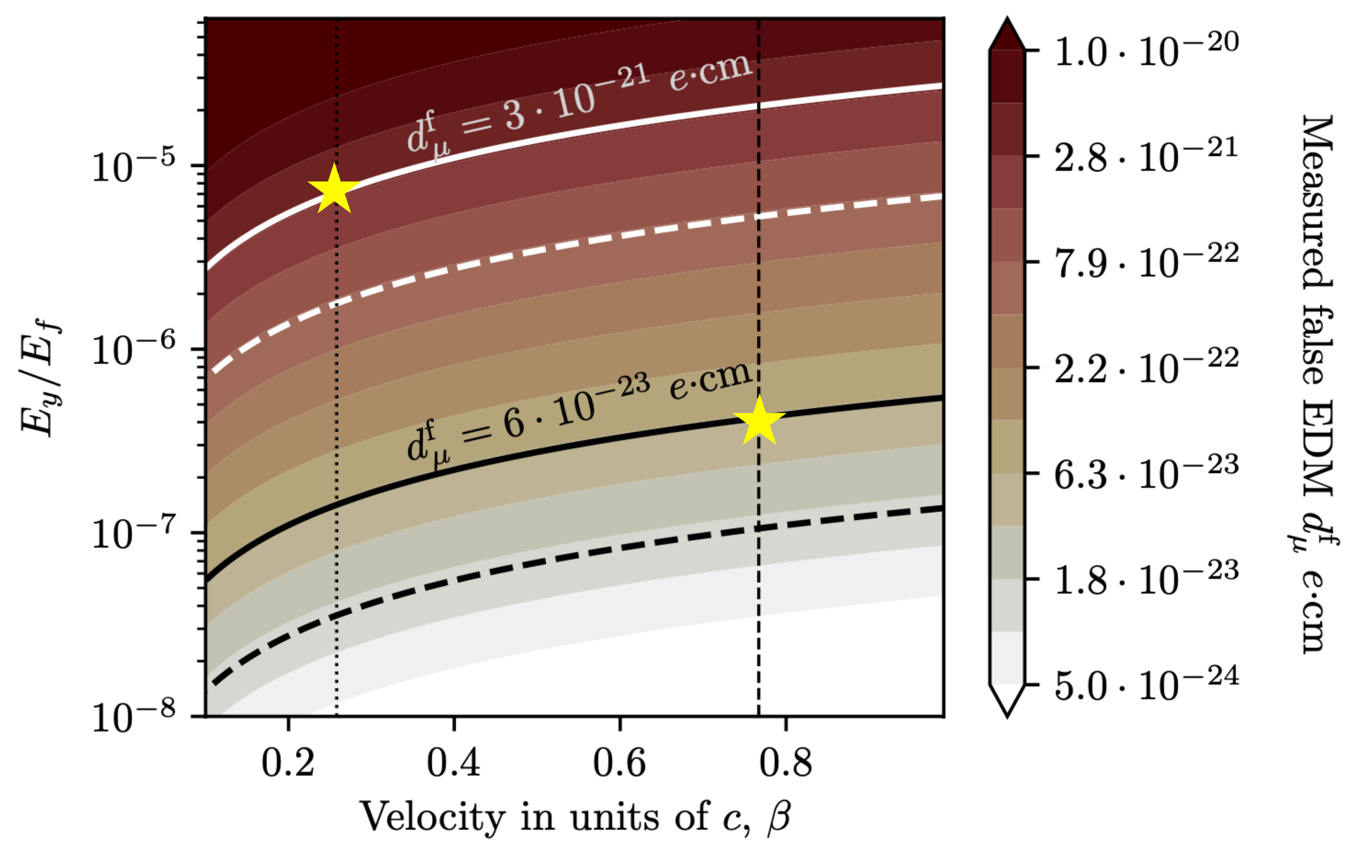



All muons
Muons that can be stored

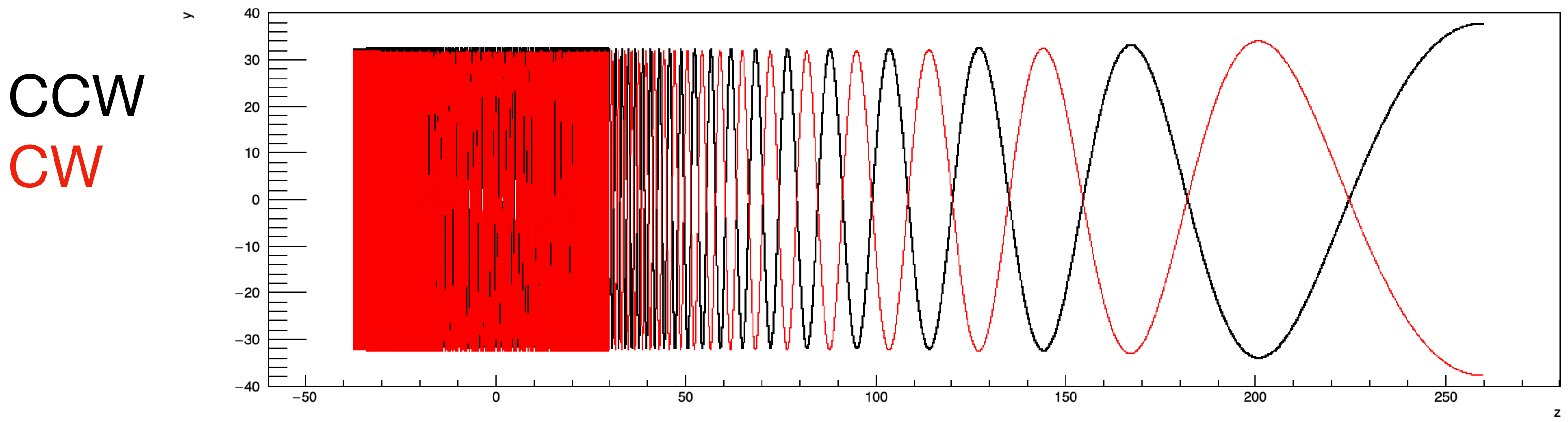
# Systematic uncertainties

$$\left\langle \left(\vec{\Omega}_{\mathrm{MDM}}\right)_x \right\rangle = \boxed{-\frac{ea}{m_0 c}\left\langle \left(1 - \frac{1}{a(\gamma^2-1)} - \frac{1}{\beta_z^2}\right)\beta_z \right\rangle \langle E_y \rangle} + \frac{ea}{m_0}\langle B_x \rangle$$

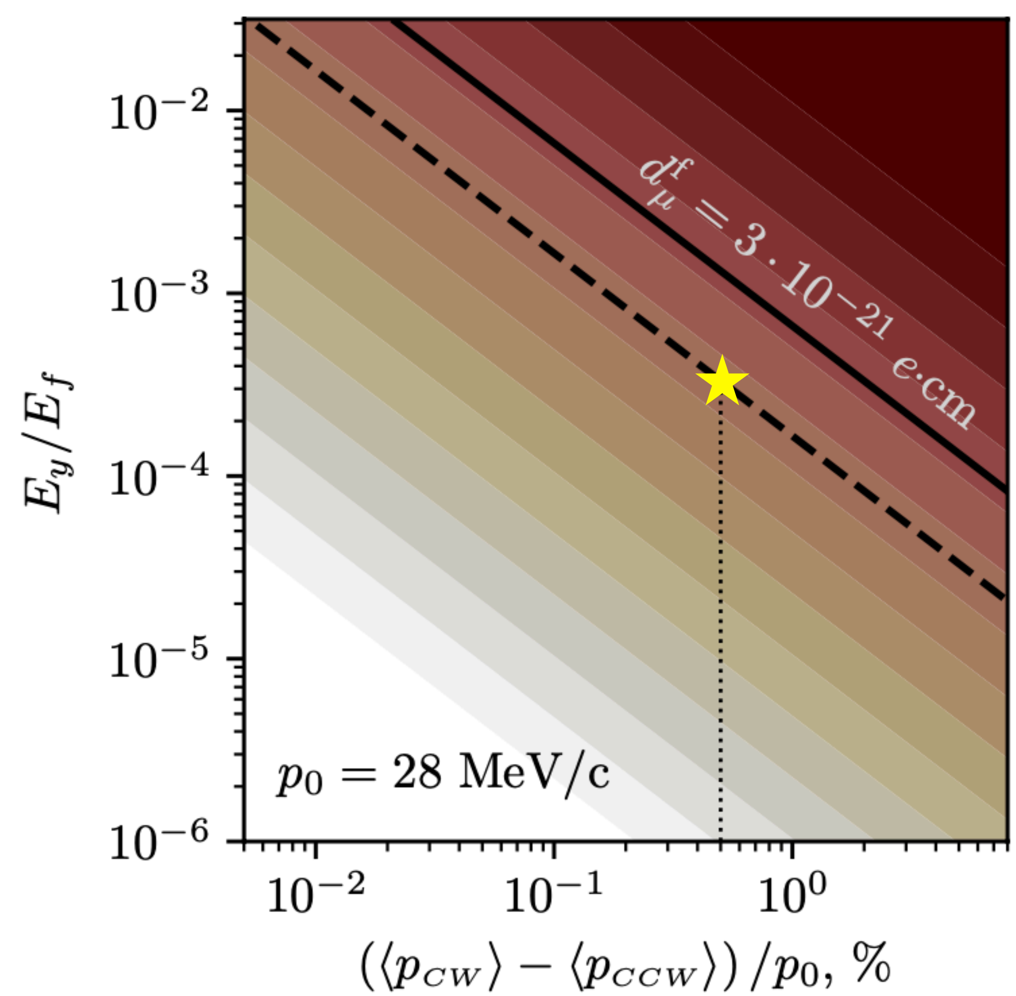
- Longitudinal components ($E_y$) in the electric field generate fake EDM-like precession
  - need to control deviations from radiality down to 1 part per $10^5$ ($10^7$) in the precursor (final) experiment **—> technically unfeasible**



# Clockwise vs. counterclockwise orbits

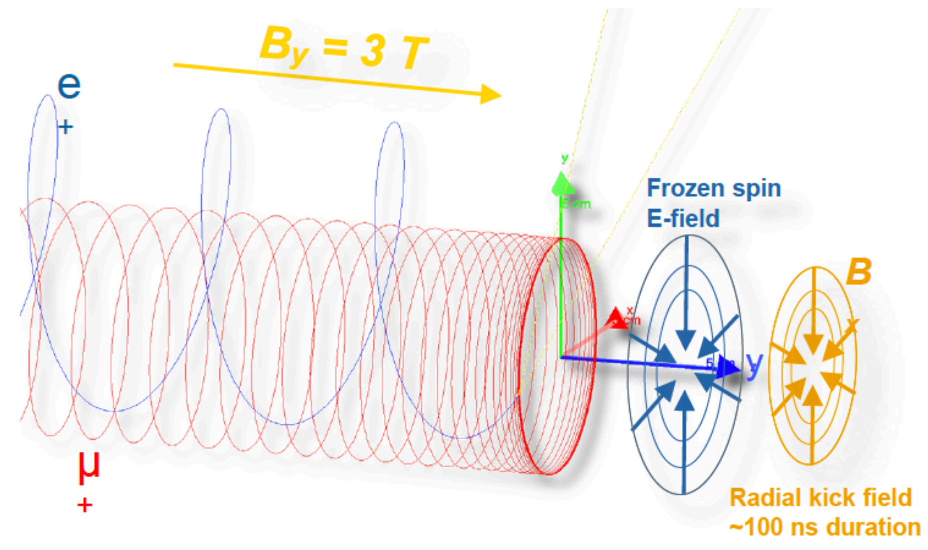



- Most systematics (including $E_y$ effects) are reversed if the magnetic field is inverted and the injection position displaced to switch between clockwise and counterclockwise orbits
  - symmetry of CW and CCW injection is required (e.g. same average momentum within 0.5% for the precursor)
  - it is necessary to directly verify that this condition is satisfied

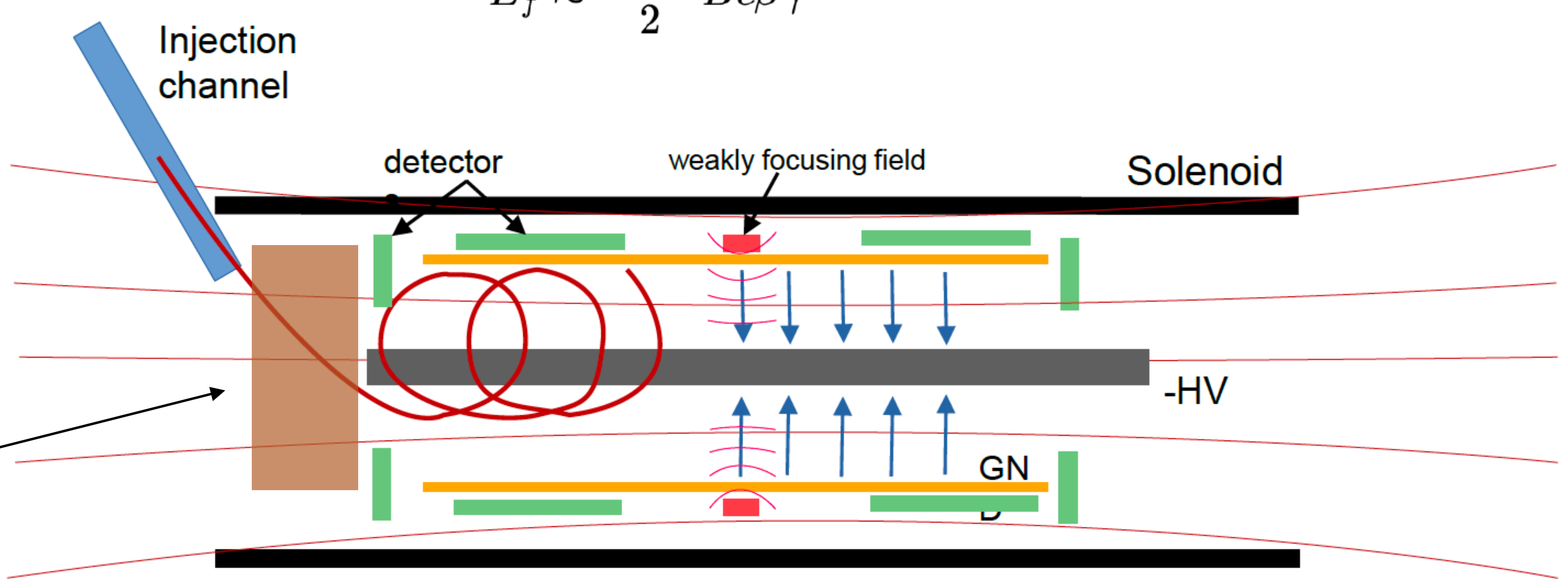


# Precision muon tracking

- A muon tracking detector to be installed **in the beam commissioning phase** (just before the physics run) and removed during the run
  - verify the consistency of the muon trajectory with the nominal one **—> efficiency**
  - verify the symmetry of CW vs. CCW injection **—> control of systematics**



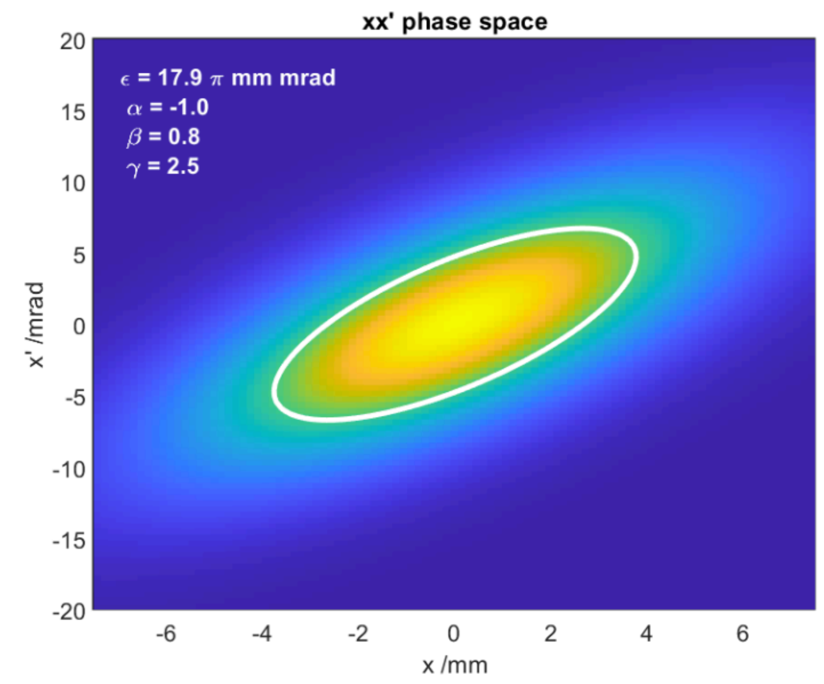

$$E_f \approx \frac{g-2}{2} B c \beta \gamma^2$$




Precision muon tracker

# Detector requirements

- Position and angular resolutions at least comparable to the phase space size —> **O(few mm x mrad)**
- Momentum resolution **O(0.5%)**

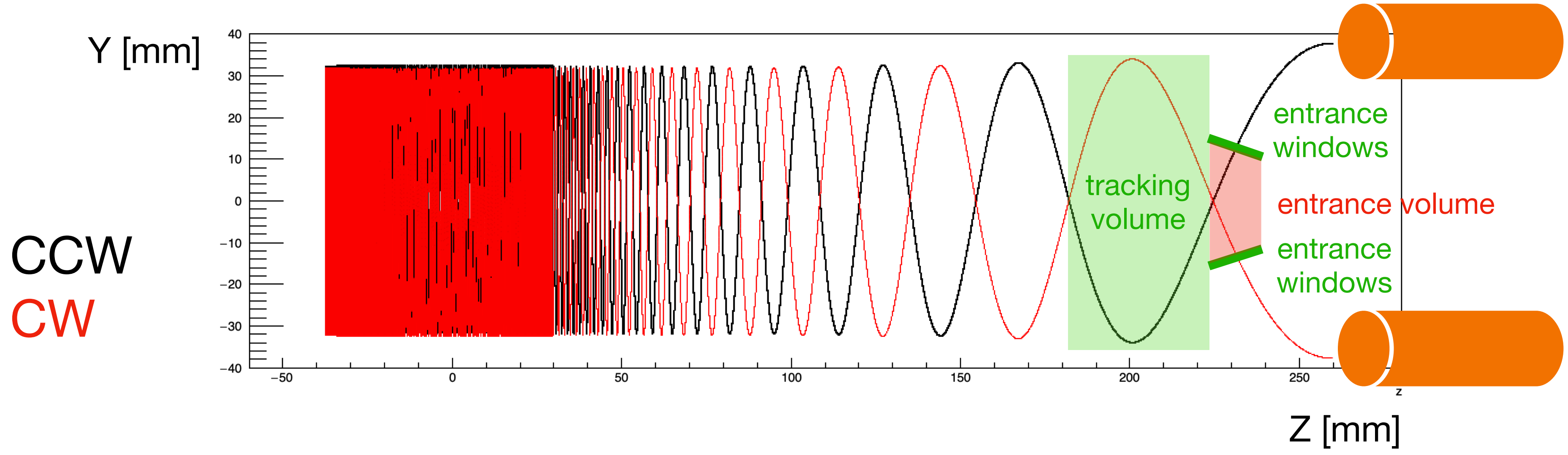



At very low momentum (28 MeV/c in the precursor experiment), the multiple scattering will play a critical role **—> extremely light detector**

Small curvature radius to be measured (25-40 mm) **—> high granularity**

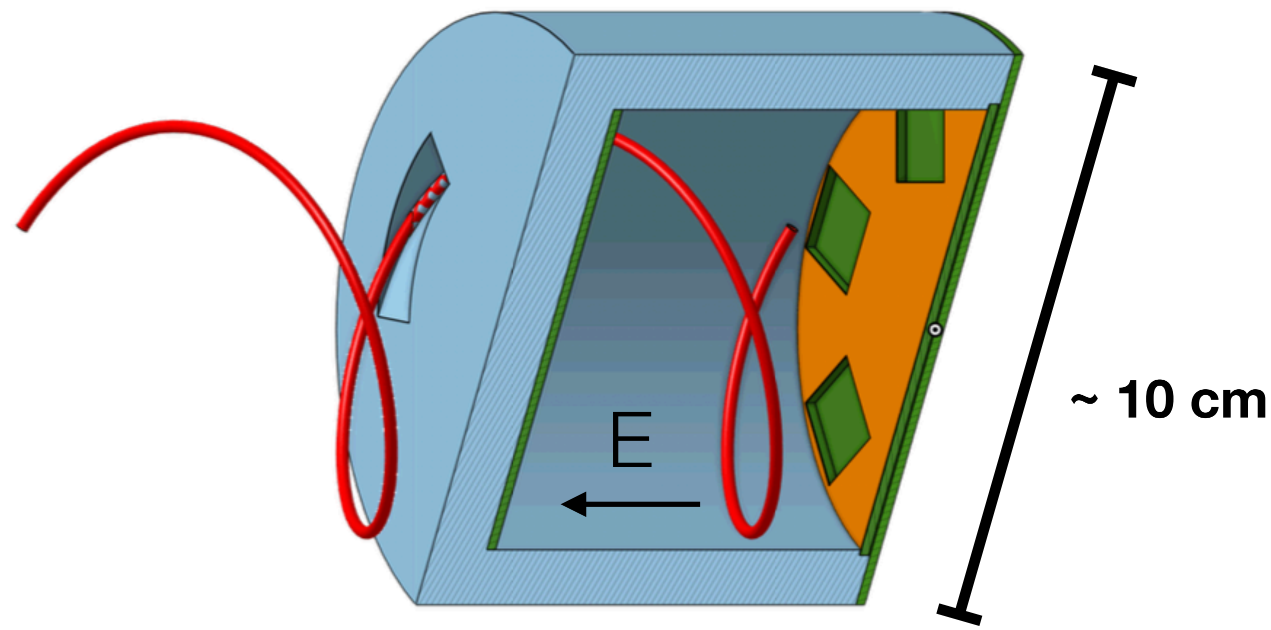
# The GridPix-TPCs

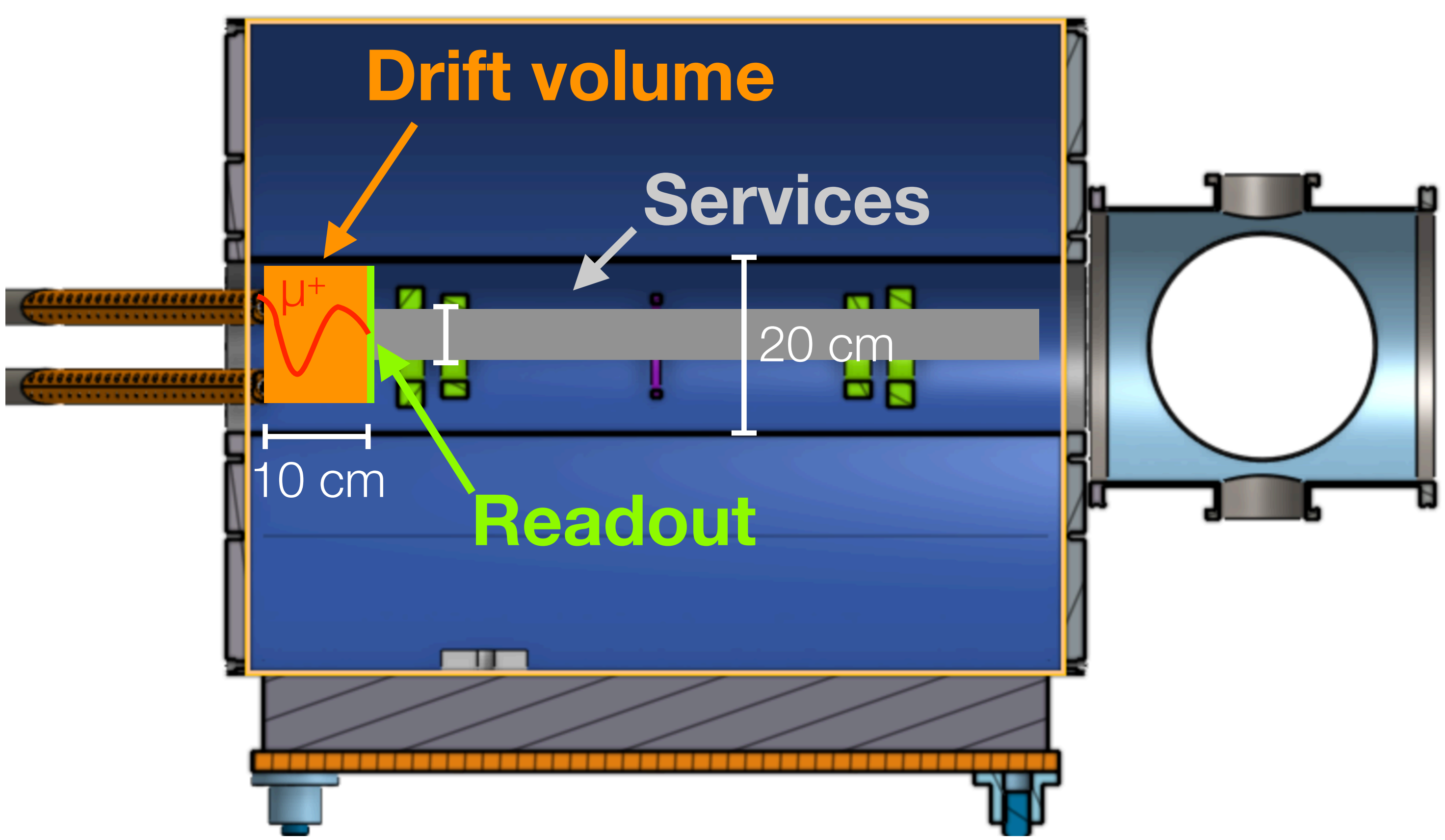
- We plan to build a gaseous **Time Projection Chambers (TPC)** readout by a **high-granularity pixelated sensor (GridPix)**
  - very light gas mixture (e.g. He:isobutane 90:10, possibly at subatmospheric pressure)
  - extremely light entrance window (400 nm silicon nitride)



# Detector conceptual design

- After having considered different layouts, we selected a conventional configuration with drift field along the main B field axis
- Optimized for momentum measurements, but angular resolutions are also competitive with alternative arrangements

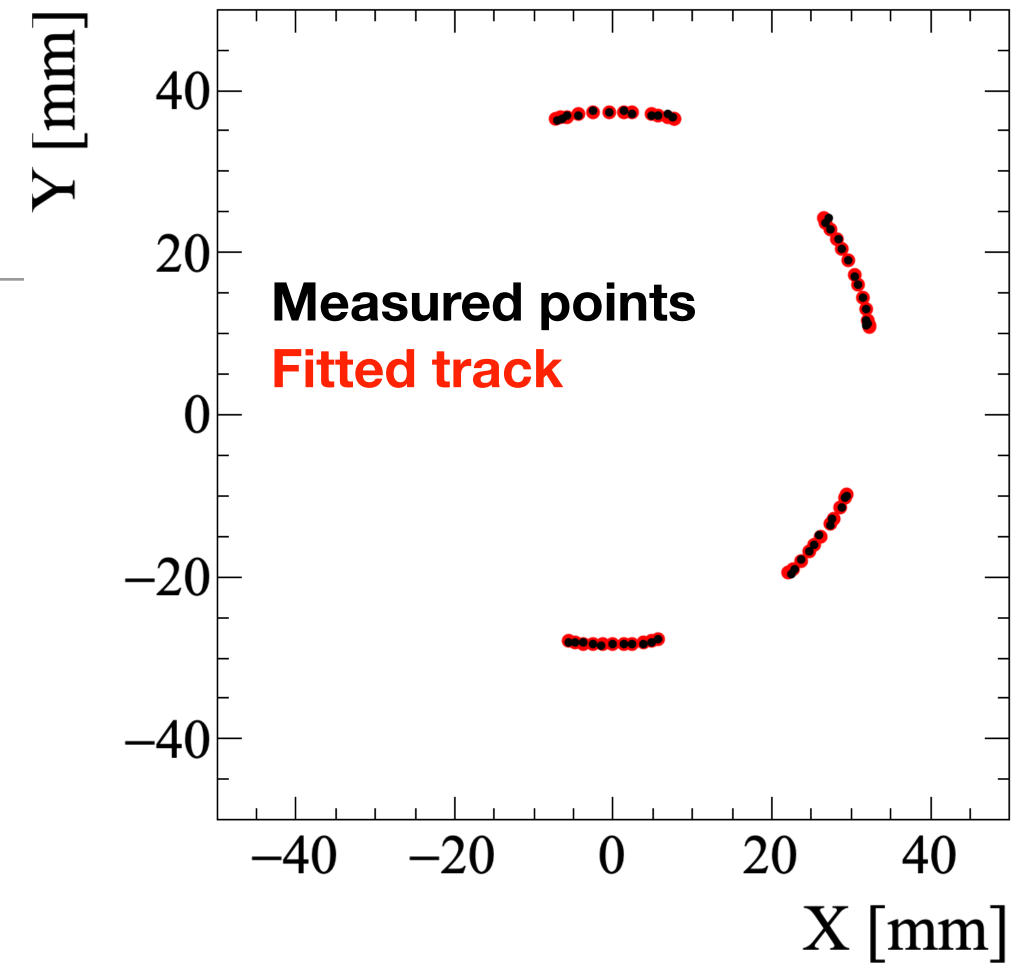


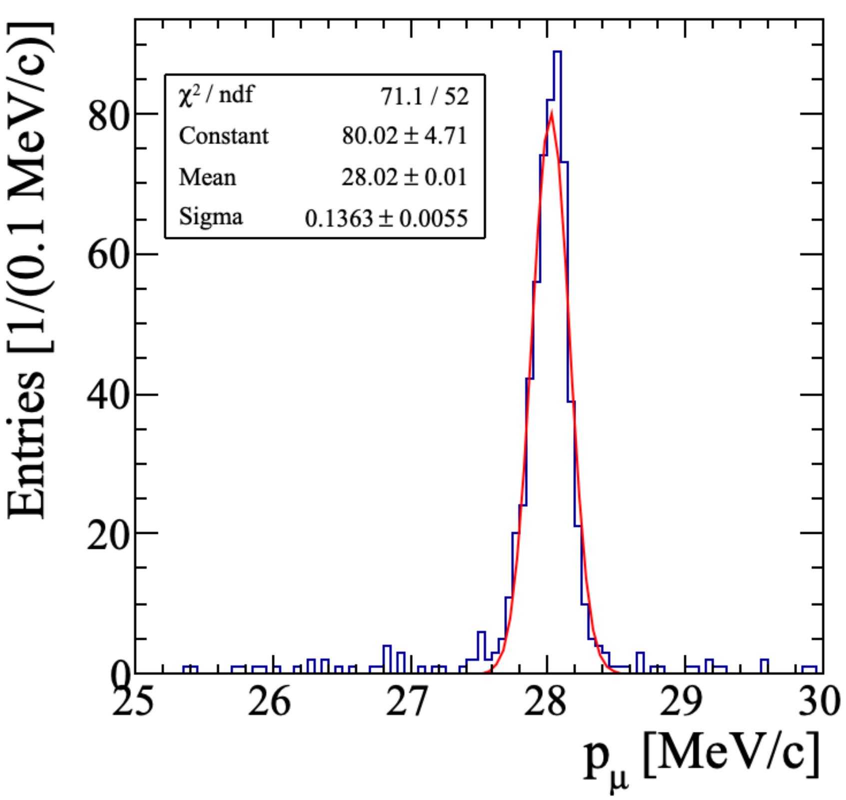

- The detector will be operated in the beam commissioning phase and removed for the precession measurements
- Still, many constraints from surrounding infrastructures
  - need to wait for a more detailed design of the experiment

# Simulations

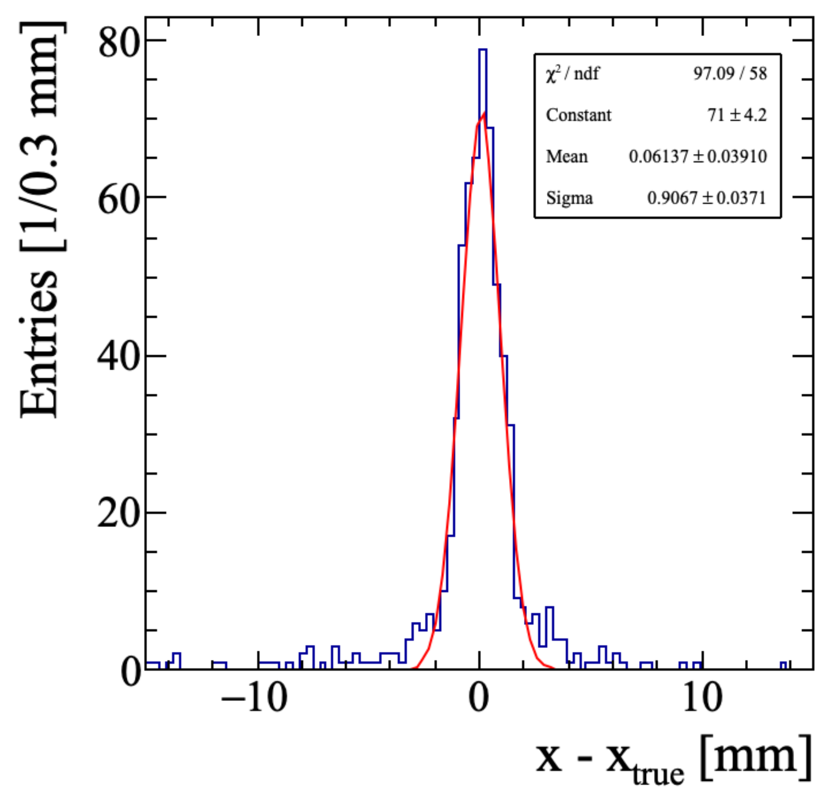
- Preliminary simulation for the radial configuration (Geometry 2 @ 1 bar), with inputs from the beam test results:
  - 0.5% momentum resolution can be achieved also in this configuration
  - angular resolution suboptimal for a full characterization of the phase space, but should be ok for alignment purposes



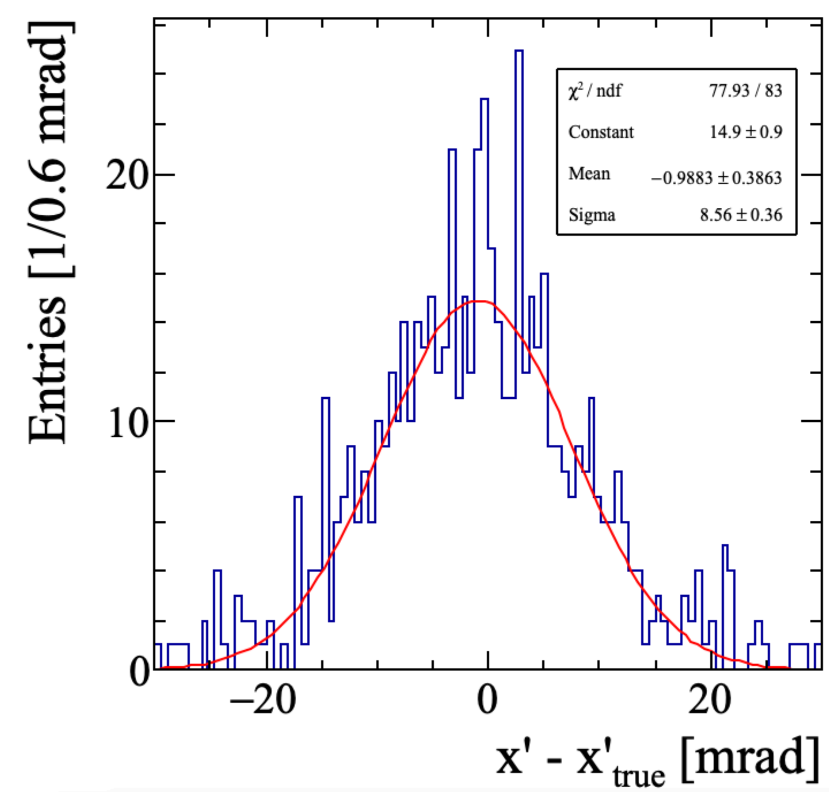

σ = 0.49%




σ = 0.9 mm

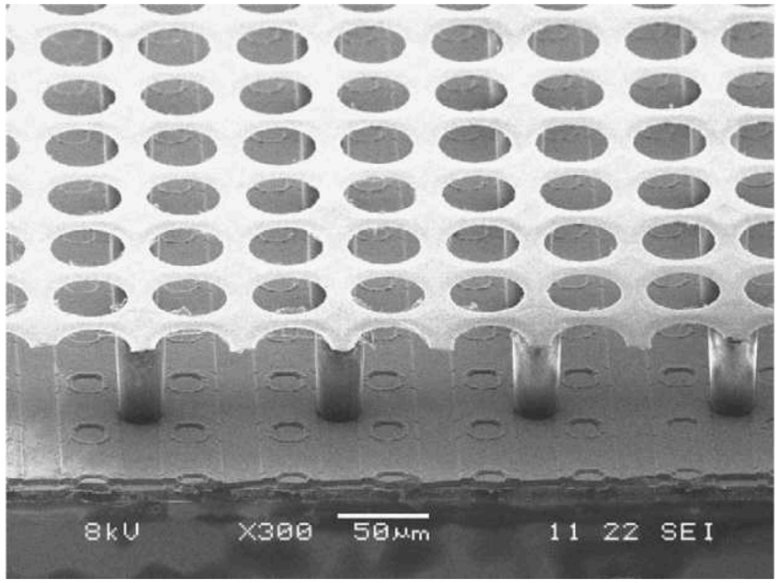


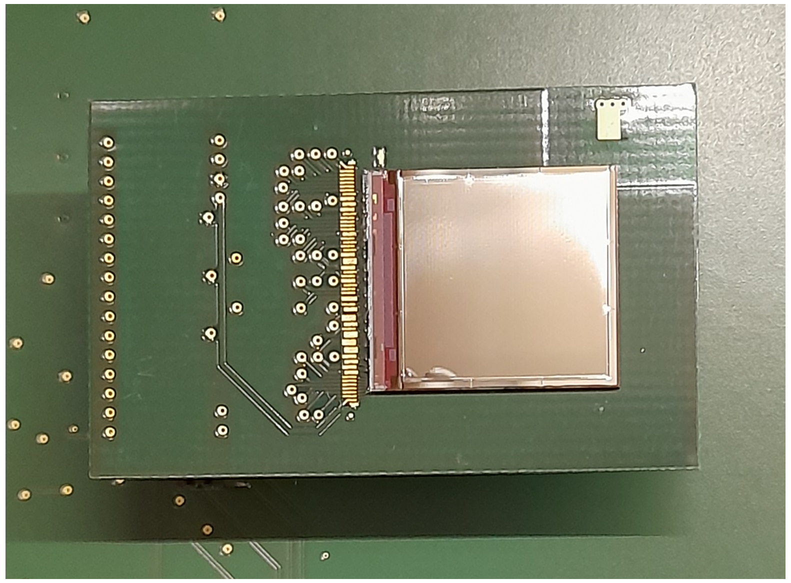

σ = 8.6 mrad

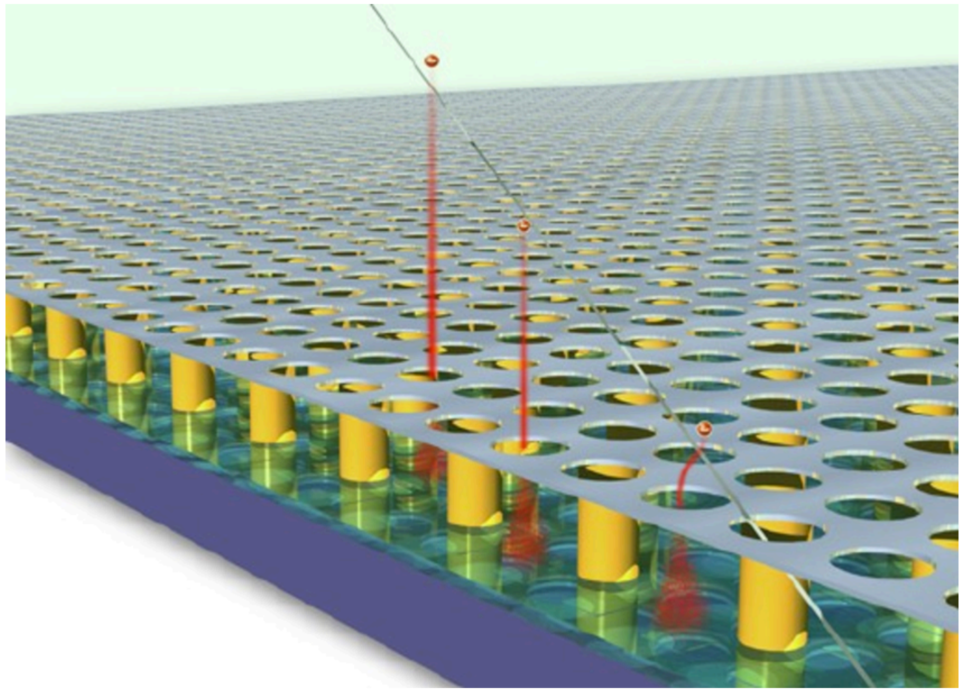


# The GridPix

- A micropattern gaseous detector, originally developed at NIKHEF
- A sort of microscopic Micromegas, with a conductive mesh built on top of a TimePix chip
    - 54 um pixels
    - holes in the mesh match the pixels with nm precision
    - single-electron detection capability
- Readout with CERN RD51 SRS electronics





# The GridPix

- A micropattern gaseous detector, originally developed at NIKHEF
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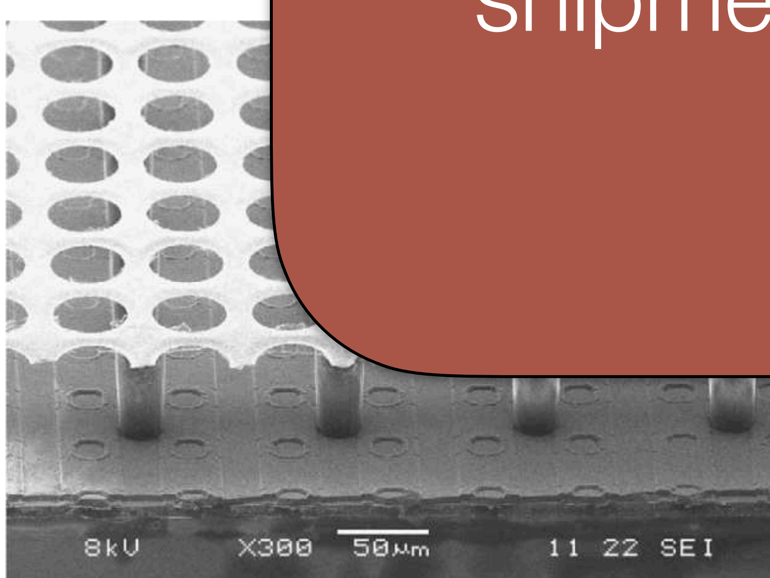
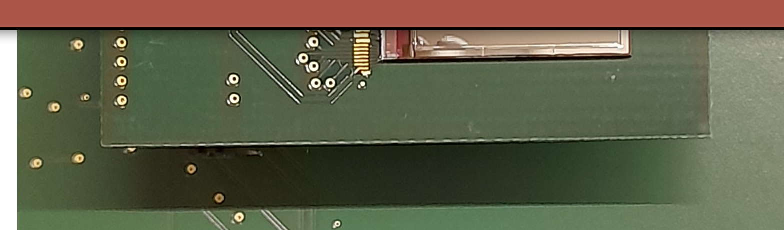
An unfortunate accident in Dec. 2023 caused the breaking of the only GridPix currently in our possession

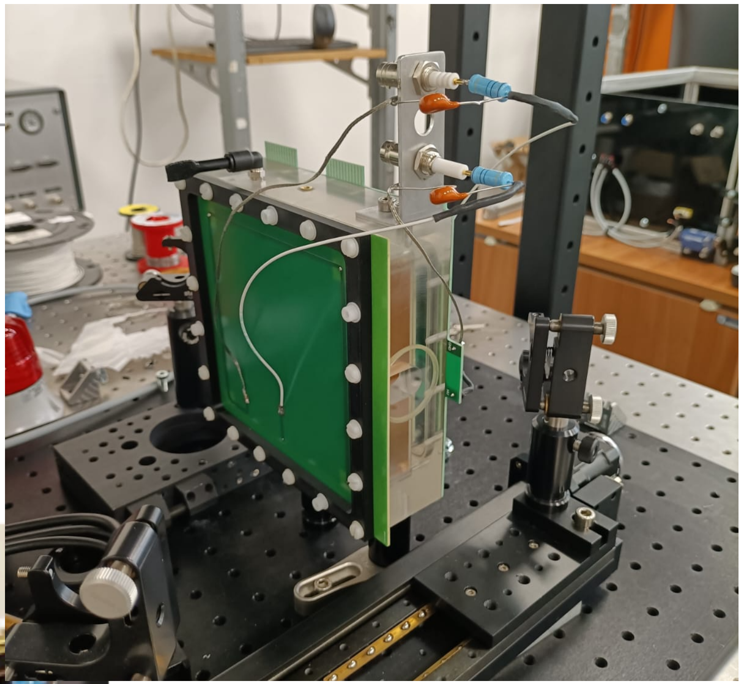
A new GridPix from Bonn Univ. ready for shipment now —> ~ 6 months delay in the programmed tests

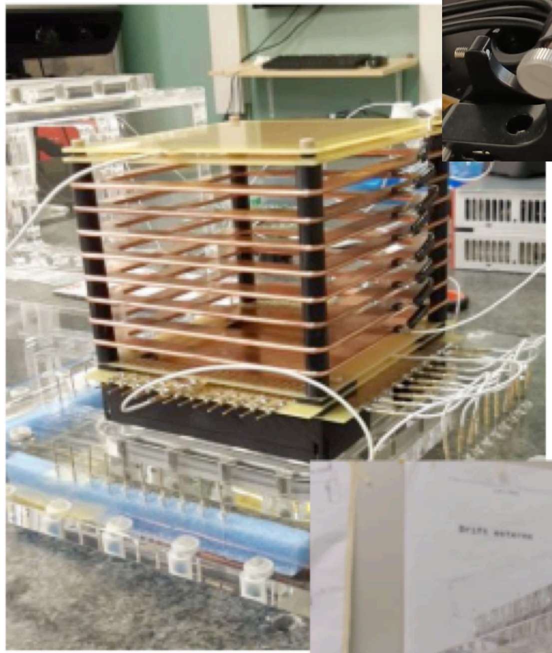


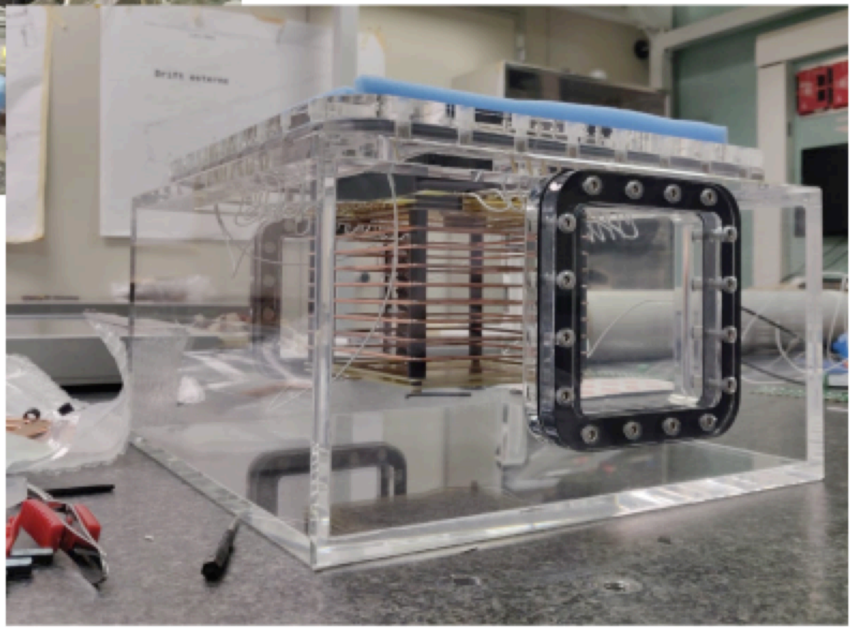



# GridPix tests

- We performed beam and lab tests in 2022-2023 to familiarize ourselves with the GridPix:
  - first characterization of the GridPix with helium-isobutane mixtures
    ***JINST* 18 (2023) 10, P10035**
- Now, we need to test the behavior under unusual conditions:
  - very high ionization rates
  - possibly, use of sub-atmospheric gas pressure
- Prototypes ready, tests will be resumed as soon as the new GridPix arrives





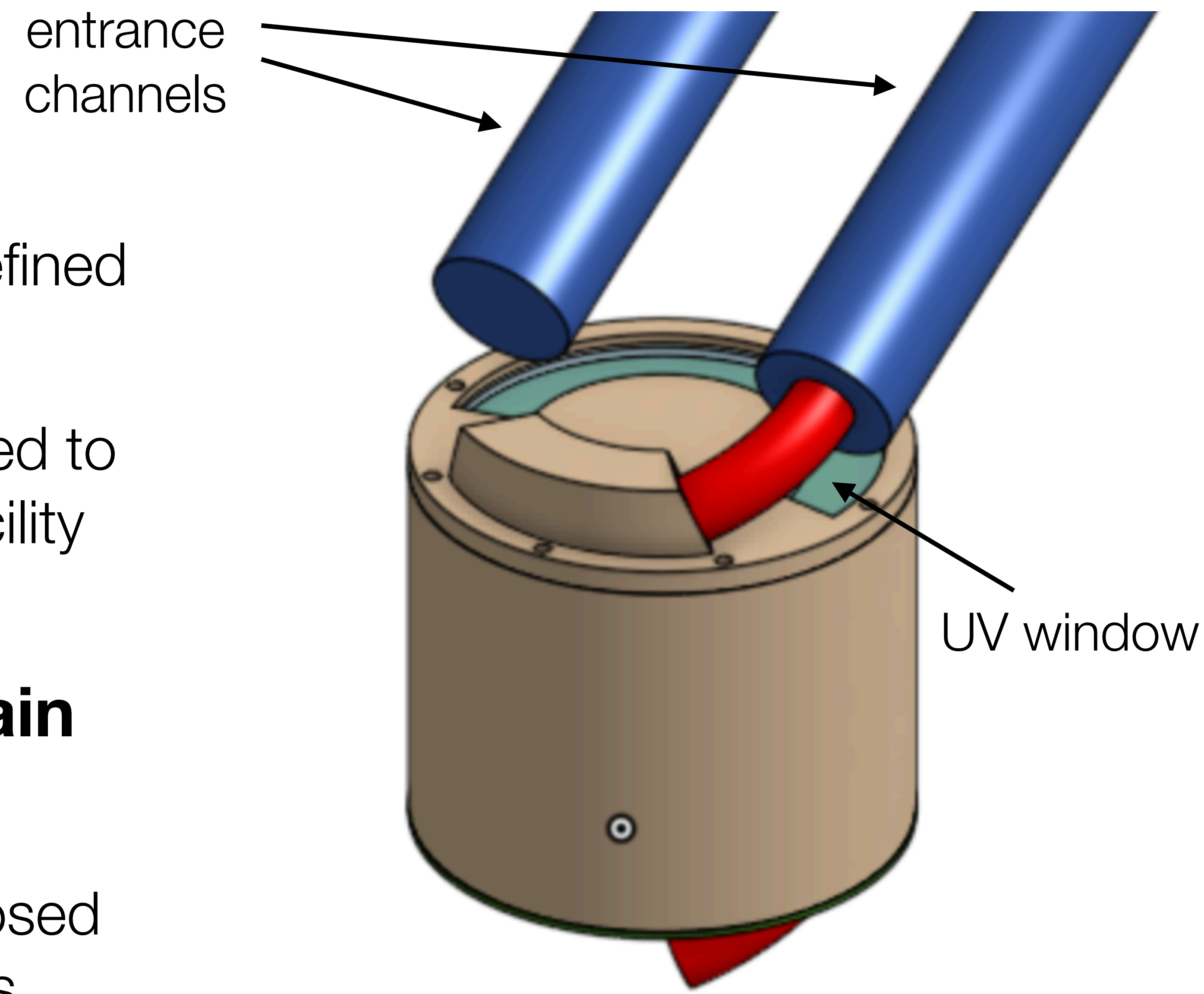


# Alternative solutions

- The current shortage of GridPix sensors is due to a severe delay in the startup of a new construction facility at Bonn University
  - the facility is expected to be fully operative in 2025 and could provide the necessary sensors for our project
- To be prepared in case of further delays, we are also considering alternative readout solutions
  - small-pad resistive Micromegas could provide the necessary rate capabilities and resolutions, with a pretty good granularity
  - simulations are promising in terms of resolutions, need to understand if granularity is sufficient to cope with high positron pileup

# Construction technologies (I)

- Detector body
  - plastic (PEEK? PE? PA?)
  - manufacturing technique to be defined (milling vs. 3D printing)
  - UV-clear windows to be considered to allow calibration with UV laser (facility available at INFN Roma)
- **Miniaturization will be the main challenge:**
  - tight geometrical constraints imposed by the dimensions of the magnet's bore in the precursor experiment

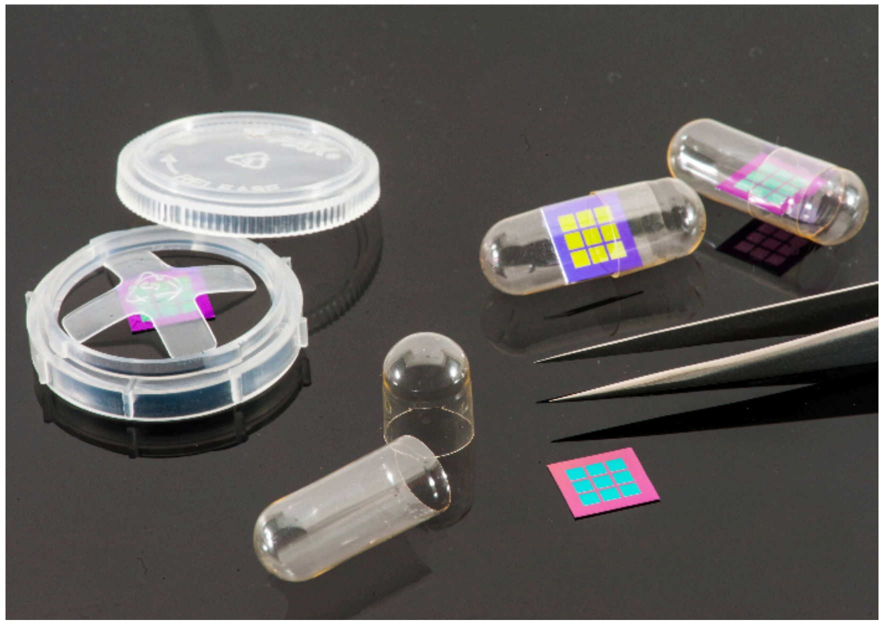


# Construction technologies (II)

- Entrance window
  - extremely light
  - helium tight and robust enough to bear 1 bar gas pressure against vacuum
  - large enough to make most of the beam passing through
  - **proposed solution: segmented, 400 nm silicon nitride membranes**
  - preliminary discussions with Silson Ltd (UK) for the production of custom segmented membranes (4.5 x 4.5 mm$^2$, 3 x 3 array)

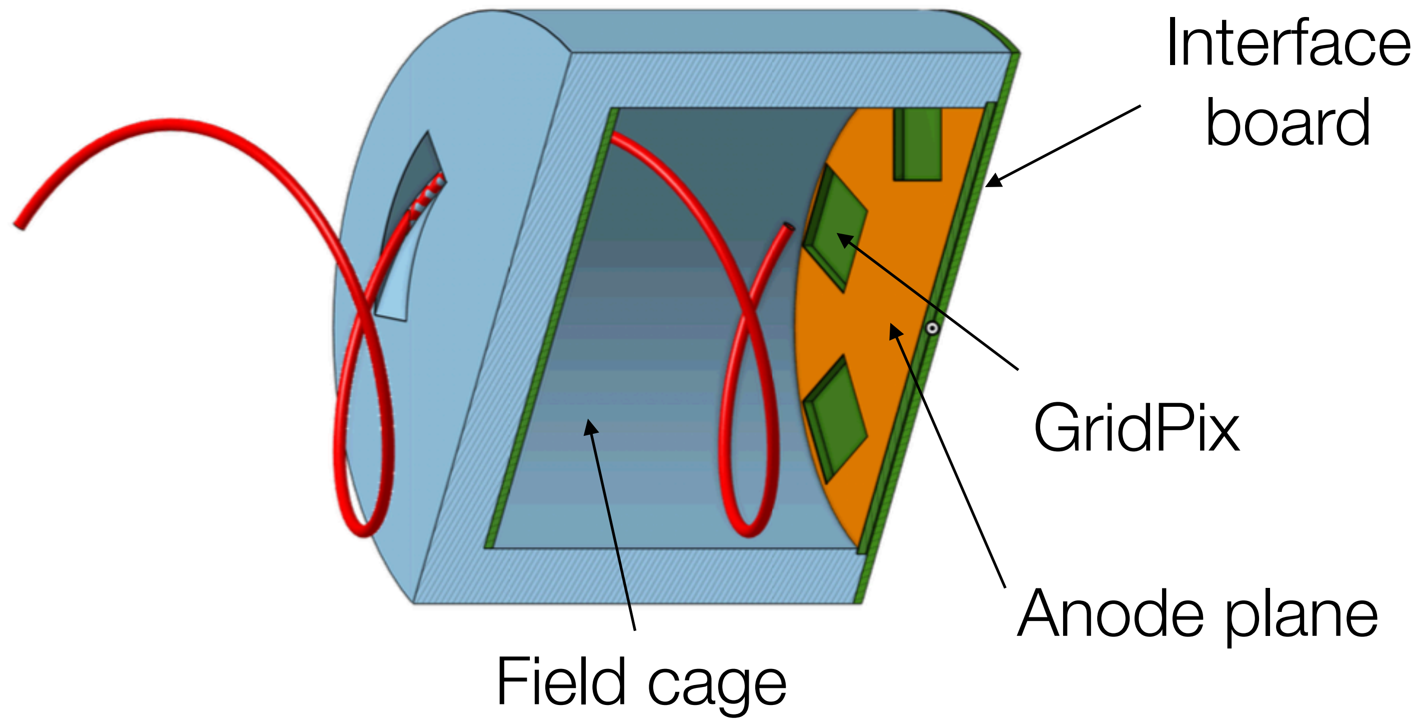
*Preliminary offer: 2.1 k€ for a set of 5*

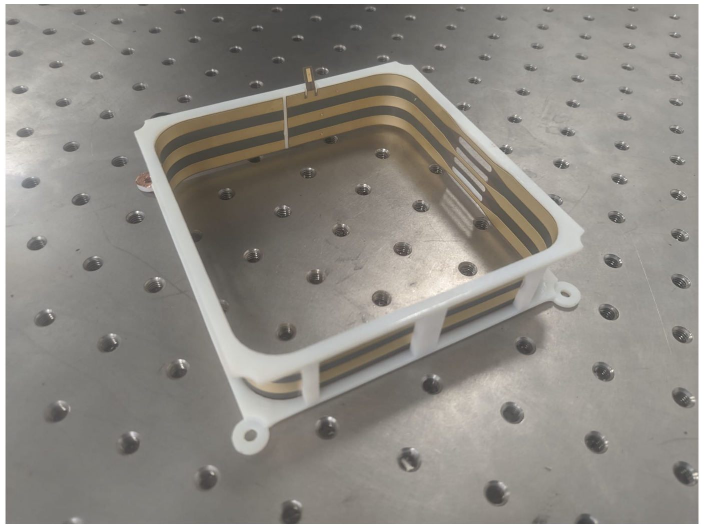
*Mounts to be designed and built in collaboration with the company*

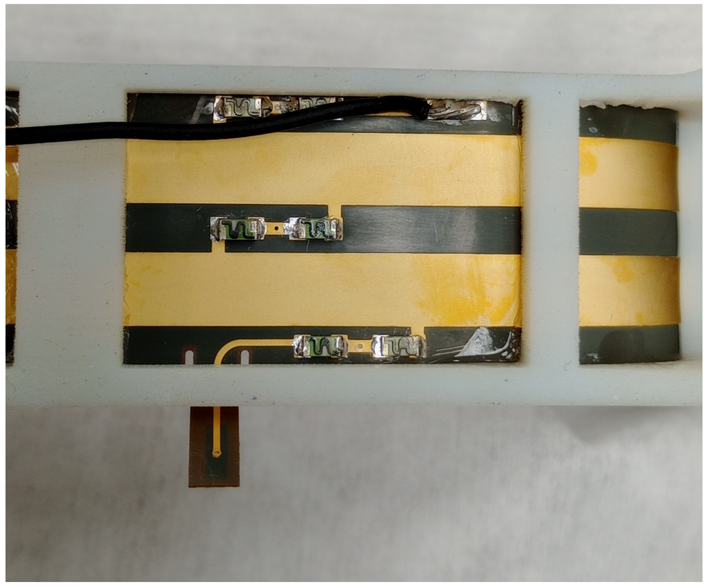


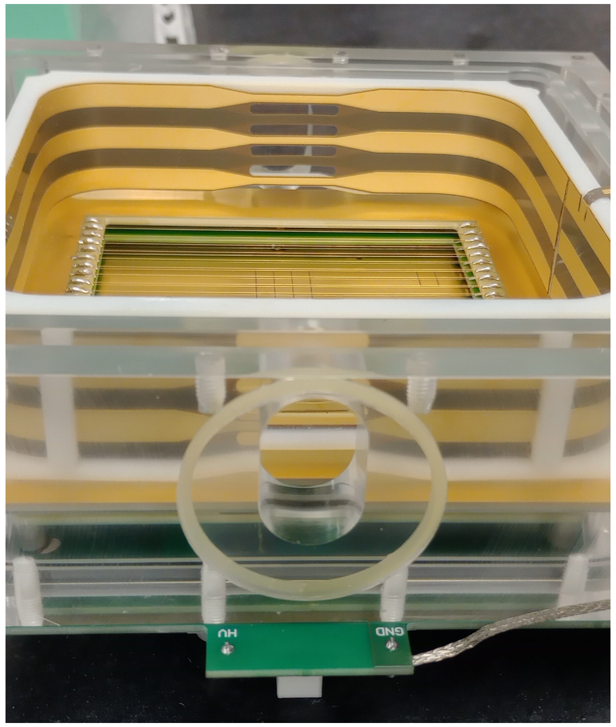
# Construction technologies (III)

- Readout planes
  - metallized anode plane + GridPix mounting and interface boards
- Field cage
  - a prototype of flexible PCB with segmented electrodes was designed, produced and tested in the last months







# Services

- These detectors are not intended for a permanent installation in the experiment **—> extensive use of instrumentation from our pools**
  - portable gas systems (2 available)
  - NIM/Desktop HV power supplies (2 available)
  - SRS electronics (1 crate + 1 FEC available —> up to 16 chips)

# Schedule

- 2024 Q1-Q2:
  - refinement of simulations
  - prototyping and test of the flexible field cage
- 2024 Q3-Q4:
  - GridPix tests at high rate and low pressure
  - finalization of the detector design
- 2025 Q1-Q2: procurement
- 2025 Q3: assembly and tests
- 2025 Q4: calibration campaign

# Anagrafica

| | | |
|---|---|---|
| G. Cavoto | Prof. Ord. | 10% |
| D. Pasciuto | Tecnologo | 10% |
| F. Renga | Primo ric. | 20% |
| C. Voena | Prof. Ass. | 10% |

- Le percentuali risentono dell’esigenza di mantenere un’opportuna copertura della presa dati MEG
  - forte sinergia tra le due sigle

# Richieste 2025 (I)

- Costruzione TPC prevista nel 2025, per avere i rivelatori pronti per il commissioning del fascio alla fine dell’anno
- Apparati:
  - Elettrodi TPC: 3 k€ — richiesta basata su costi sostenuti per i prototipi
  - Servizi TPC (cabling, piping, etc.): 3 k€
  - Ottiche per sistema calibrazione laser: 1 k€ — da prezzi di listino
  - Mecchanica TPC: 10 k€ — da offerte preliminari incl. prototipi e mockup
  - Small-pad resistive Micromegas: 10 k€ — SJ alla necessità di rimpiazzare i GridPix, riserva da scogliere entro fine 2024

# Richieste 2025 (II)

- Consumo:
  - Gas per test muonTPC: 3 k€ — 3 x He 6.0 50 litri + 1 x iC4H10 25 kg + 1 x CO2 50 litri, secondo offerte per acquisti recenti

- Missioni:
  - 3 collaboration meeting x 2 persone: 5 k€
  - 2 settimane al PSI per test beam x 2 persone: 5 k€