Test Beam results of planar GEMs with analog and time readout in strong magnetic field and very high rate

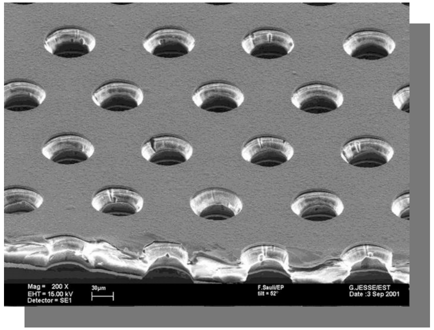
Riccardo Farinelli
on behalf of BesIII Italian Collaboration

Outline

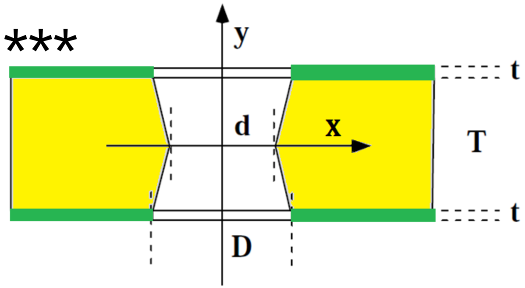
- Triple-GEM technology
- Position reconstruction methods
- Test Beam @ H4 – CERN and magnetic field results
- Test Beam @ MAMI – Mainz and high rate results

Gas Electron Multiplier *

- **Triple-GEM technology**
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- High rate TB @ MAMI - Mainz

** 

- polymeric foil (kapton, T = 50 μm)
- copper coated (t = 3/5 μm)
- pierced by thousands of holes (d ~50 μm)

*** 

- One or more GEMs are placed within anode and cathode, in gas
- Hundred of Volts applied on the two copper faces of the GEM and an electric field of some tens of kV/cm is generated in the holes
- Electron entering in the hole creates an electron avalanche

* Invented by F.Sauli in 1997 ** **Picture** of a GEM foil *** **Schema** of the GEM hole

Triple-GEM technology

- **Triple-GEM technology**
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- High rate TB @ MAMI - Mainz

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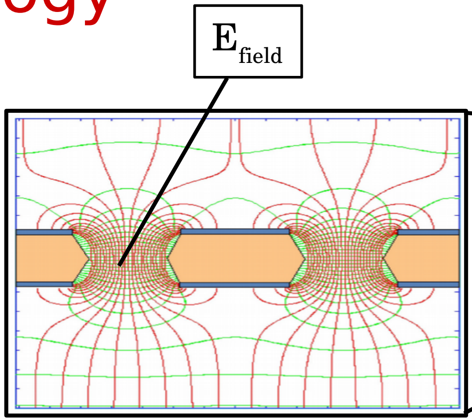

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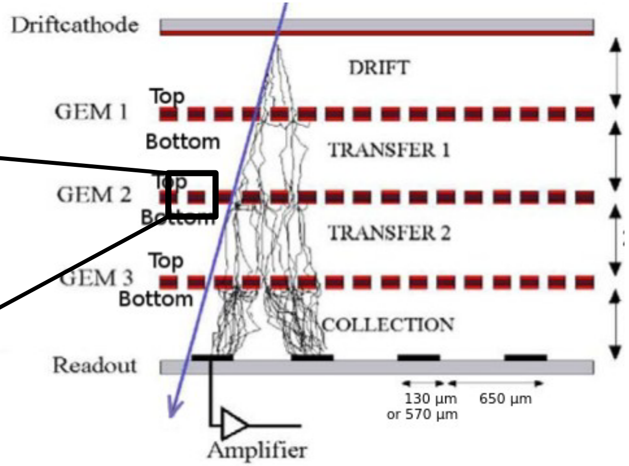

- Three amplification stages allow the triple-GEM to reach a gain of ~ 10^3-10^4 while the discharge probability is below 10^{-5}
- The signal collected at the anode depends by the gas mixture, the geometries and the involved fields.

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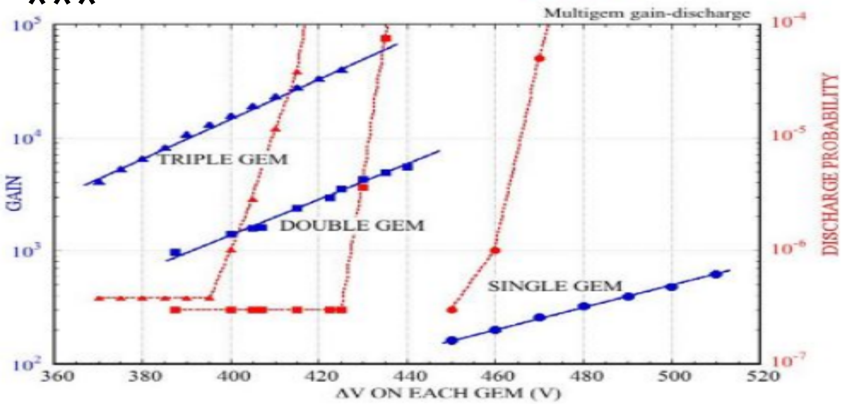


* **Schema** of the electric field around the GEM hole

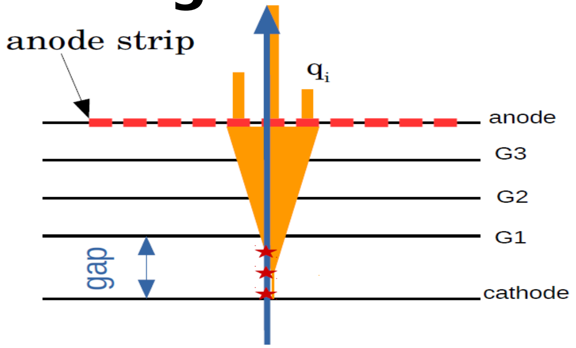
** **Schema** of the electron multiplication in a triple-GEM

*** **Gain and discharge** probability from literature

Position reconstruction methods

- Triple-GEM technology
- **Position reconstruction methods**
- Magnetic field TB @ H4 - CERN
- High rate TB @ MAMI - Mainz

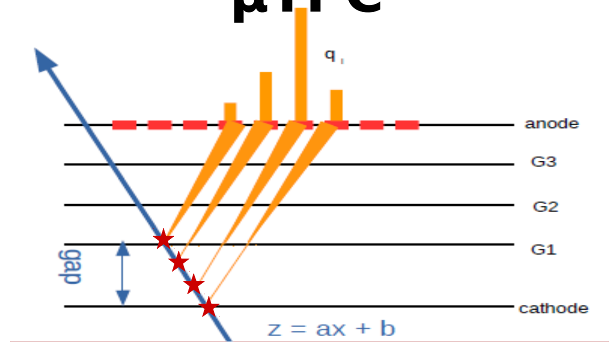
Charge Centroid



The position is reconstructed as weighted average of the fired strips by the charge on each strip

$$< x > = \frac{\sum_i x_i q_i}{\sum_i q_i}$$

µTPC*



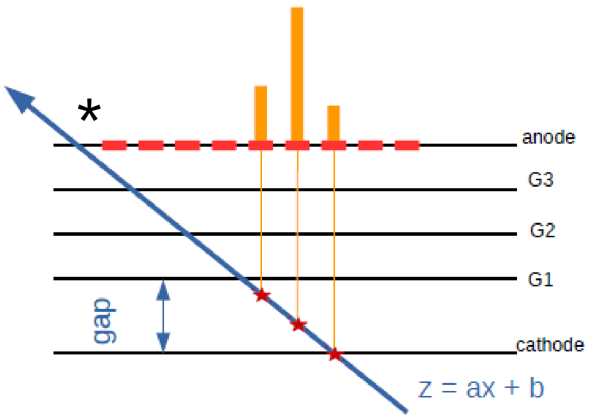
Use the drift gap as a "*micro* time projection chamber" and reconstruct the position of **each primary ionization** by the electron drift velocity

$$x = \frac{\frac{gap}{2} - b}{a}$$

* [T. Alexopoulos *et al*, NIM A617 (2010) 161]

Position reconstruction methods

- Triple-GEM technology
- **Position reconstruction methods**
- Magnetic field TB @ H4 - CERN
- High rate TB @ MAMI - Mainz



* **Schema** of the µTPC reconstruction

Input for µTPC reconstruction:

1. **x coordinate** of each firing strip (from measurement)
2. **drift time** of each primary ionization (from measurement)
3. **drift velocity** of the electrons (from GARFIELD simulation)

- **It assigns to the strips a bi-dimensional point** (x_strip, time * drift velocity).
- These points are used to reconstruct the track in the drift region
- **A linear fit reconstructs the path** and measures the particle position

Test beam @ H4 - CERN

Magnetic field test @ H4-CERN: Setup & aim

- Triple-GEM technology
- Position reconstruction methods
- **Magnetic field TB @ H4 - CERN**
- High rate TB @ MAMI - Mainz

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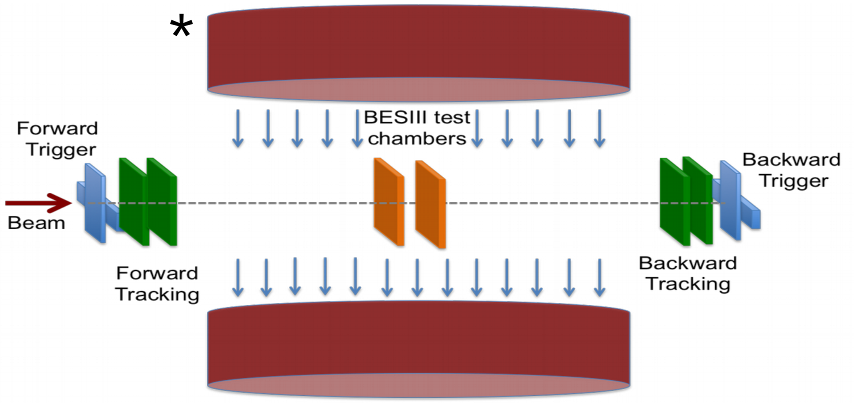

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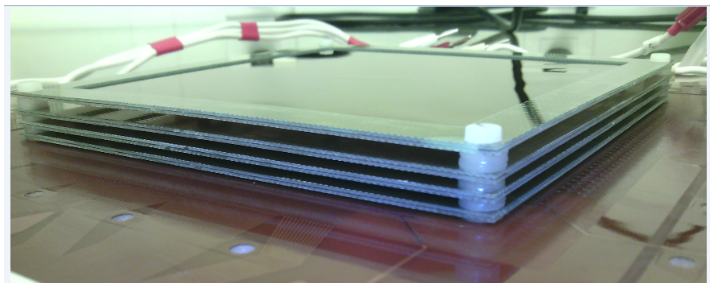


- The triple-GEM characterized have 3 or 5 mm gap in the drift region and 2 mm in the others.
- The pitch size of the strip is 650 µm and a 2-D readout
- A muon and pion beam @ H4-CERN has been used
- The dipole magnet Goliath can reaches 1.5 T in both polarities
- The gas mixtures used are Argon based: Ar/CO_2 (70/30) and Ar/iC_4H_{10} (90/10)
- The aim of this TB is measure the performances of a triple-GEM in magnetic field

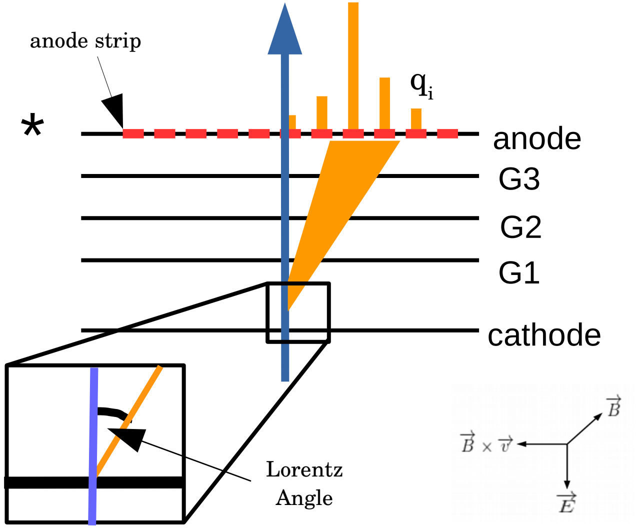
* **Schema** of the TB setup with trigger, trackers, dipole magnet and test chambers

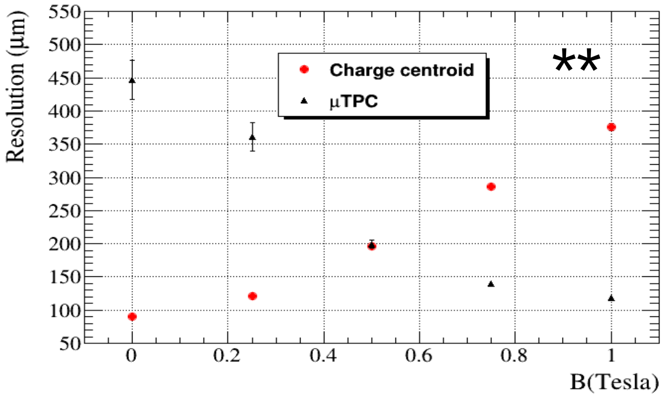
** **Picture** of a triple-GEM outside the gas box

Magnetic field test @ H4-CERN: CC & µTPC vs B.field

- Triple-GEM technology
- Position reconstruction methods
- **Magnetic field TB @ H4 - CERN**
- High rate TB @ MAMI - Mainz

- The magnetic field affects the electronic avalanche:
  - the Lorentz force drifts the electrons,
  - the magnetic field enlarges the charge distribution at the anode and the multiplicity largely increases,
  - ➔ the charge distribution of the charge is **no longer Gaussian** and the charge centroid performance degrades
  - ➔ µTPC reaches its best performance when the **multiplicity** is sufficiently large





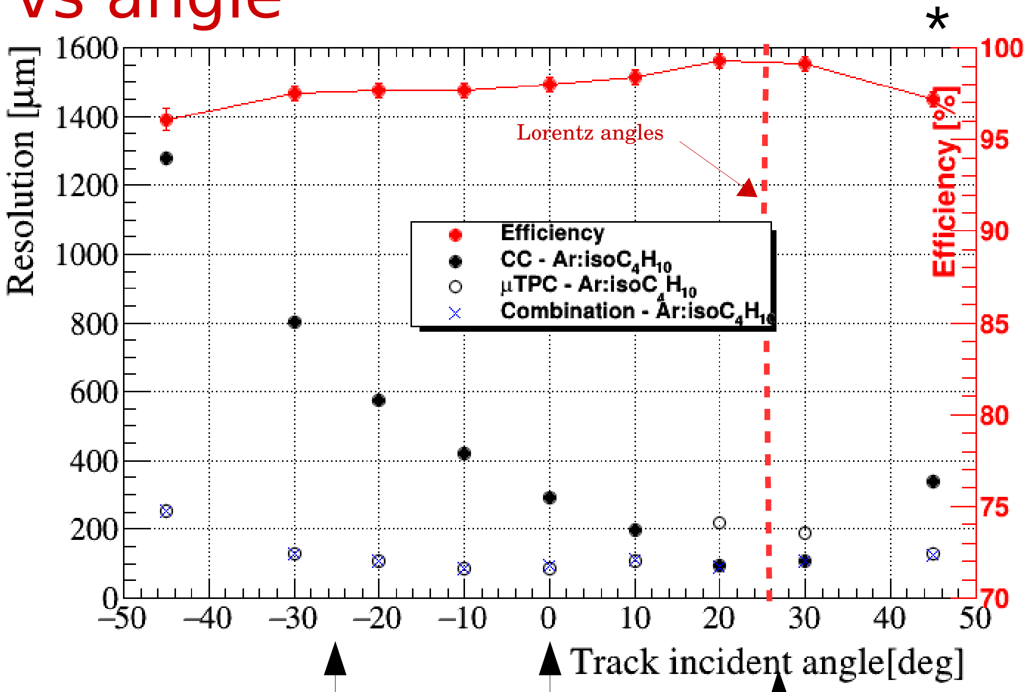
* **Schema** of the avalanche drift in a triple-GEM

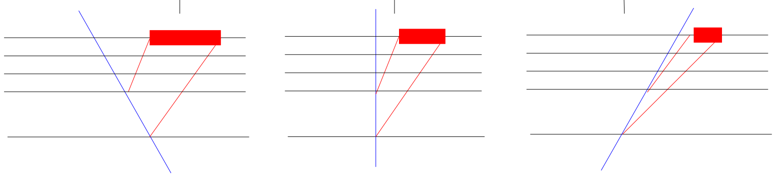
** **B scan**
5 mm conversion gap
820V on the GEMs
$Ar:iC_4H_{10}$
1.5 kV/cm drift field
orthogonal track

Magnetic field test @ H4-CERN: CC & µTPC vs angle

- Triple-GEM technology
- Position reconstruction methods
- **Magnetic field TB @ H4 - CERN**
- High rate TB @ MAMI - Mainz

- µTPC has to take into account the Lorentz angle to reconstruct the tracks with the magnetic field. That angle is calculated with simulations.
- The Lorentz angle with Ar:iC_4H_{10} @ 1,5 kV/cm drift field is ~ 26°. In this region CC is more efficient. In the other regions µTPC is flat around a resolution of ~100 µm
- A **combination of the two methods should keep the resolution stable** in the full range of incident angles





* **Angle scan**
5 mm conversion gap
820V on the GEMs
Ar:iC_4H_{10}
1.5 kV/cm drift field
1 T magnetic field

Test beam @ MAMI - Mainz

High rate test @ MAMI: The Setup

- Triple-GEM technology
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- **High rate TB @ MAMI - Mainz**

- Four triple-GEMs have been tested at the MAMI facility in Mainz
- The beam size is about few mm²
- A rate up to few 10^7 Hz/cm² has been used to perform the test
- The aim of this TB is to study the μTPC variables as the drift velocity

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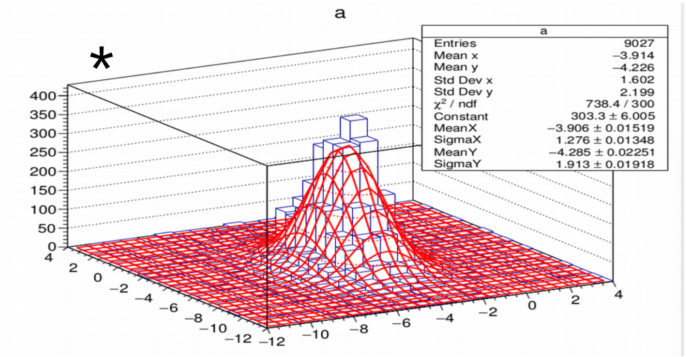

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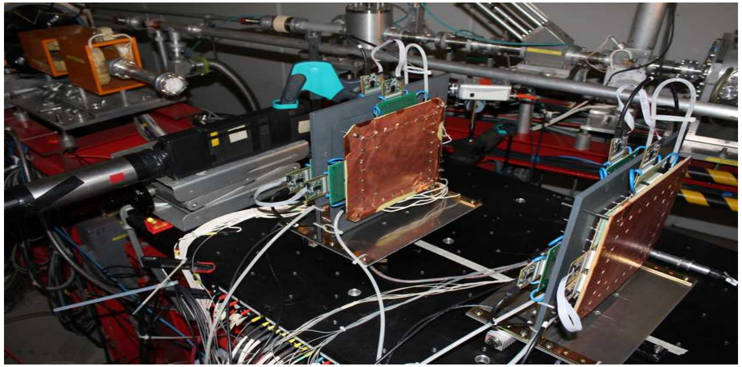

* **Beam profile**
30° angle track
820V on the GEMs
Ar:iC_4H_{10}
2 kV/cm drift field
no magnetic field

** **Picture**
MAMI setup

High rate test @ MAMI: What changes with **high rate**

- Triple-GEM technology
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- **High rate TB @ MAMI - Mainz**

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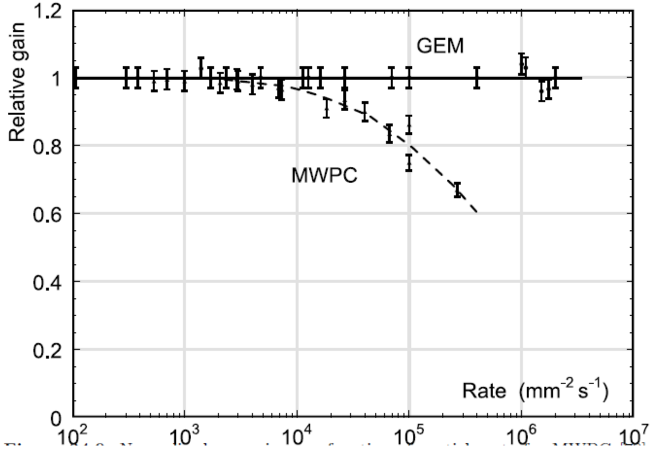
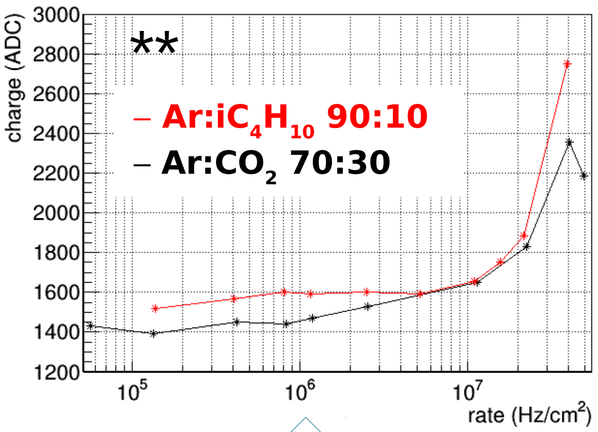


- In **every gas detector**, when a ionization happens, the **electron and positive ion drift** along the electric field lines
- The **electron** drift velocity is high → **fast signal**
- The **ions** mobility is lower → at high rates there might be **accumulation of positive charge** in the detector.
- The **space charge issue** may create:
  - **distortion of the electric field**
  - reduction of the gain
  - degradation of spatial resolution & aging
- The rate **limit:**
  - for a **wire detector** is **10^3 Hz mm^{-2}**
  - for **GEM** is **much higher!**

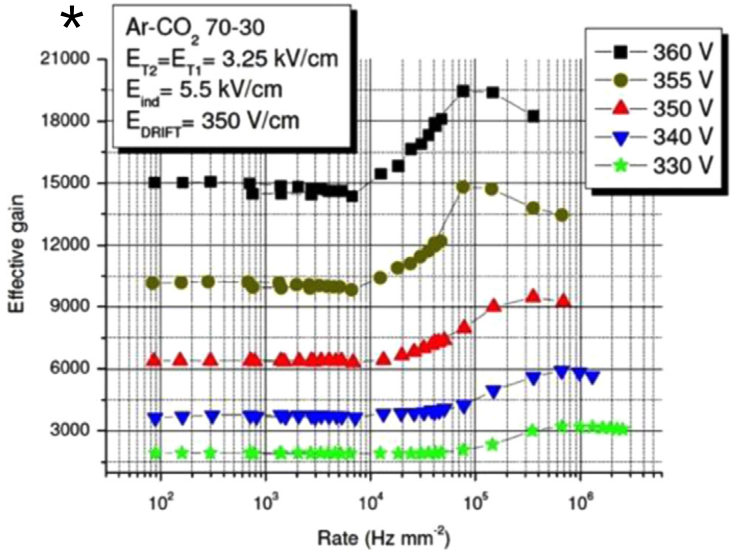
* [http://pdg.lbl.gov/2016/reviews/rpp2016-rev-particle-detectors-accel.pdf]

High rate test @ MAMI: **Charge** vs Rate

- Triple-GEM technology
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- **High rate TB @ MAMI - Mainz**



The cluster mean charge is constant up to 10^6 Hz/cm^2, then it increases up to 10^7 Hz/cm^2 and eventually drops



This behavior resembles the result reported in fig. 43 of F.Sauli's GEM Review of 2015

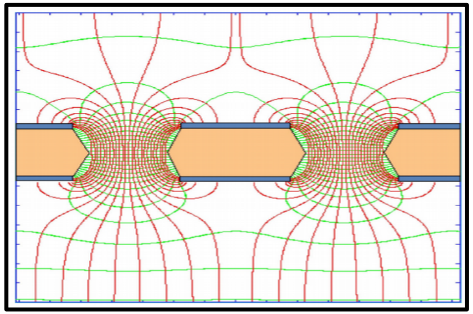
The field/HV settings are **different**!

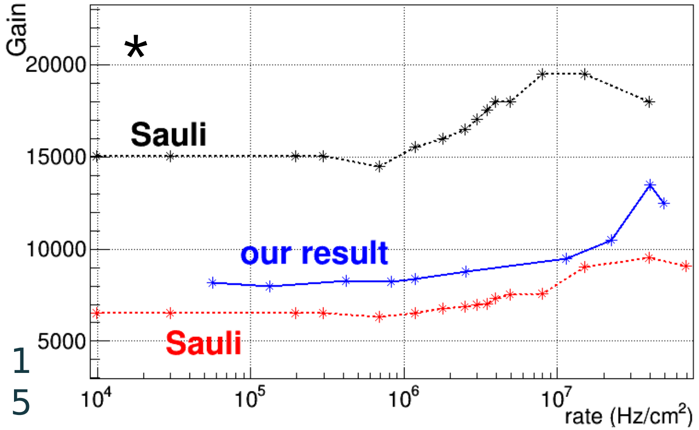
* [F.Sauli NIM A805 (2016) 2–24 15l]

** **Gain**
30° angle track
5 mm drift gap
~ 10k gain
Ar:CO²
no magnetic field

High rate test @ MAMI: **Gain** vs Rate

- Triple-GEM technology
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- **High rate TB @ MAMI - Mainz**





- The charge *vs* rate was scaled to plot the gain *vs* rate
- The curves from Sauli at a similar gain/HV have been *copied* into the same graph

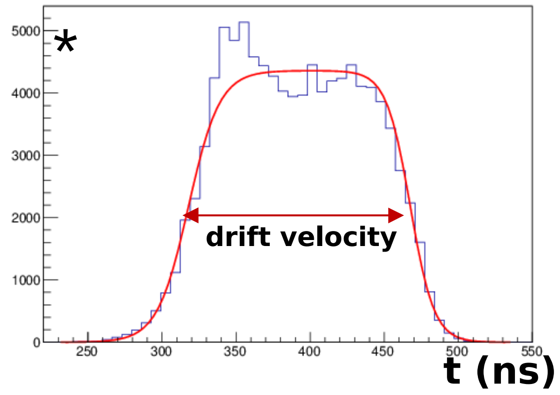
- The resulting behaviors are comparable.
- The gain is
  - **stable** up to 10^6 Hz/cm^2
  - it **increases** up to 10^7 Hz/cm^2
  - it **drops** afterwards

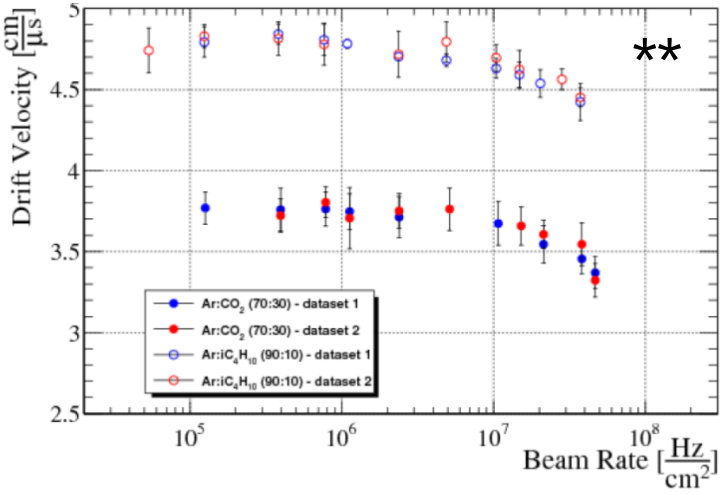
- An explanation is given in [P. Thuiner CERN-THESIS-2016-199]: **the space charge** due to the positive ions modifies the electric field and **increases the transparency of the GEM**

* **Gain + Literature**
30° angle track
5 mm drift gap
~ 10k gain
Ar:CO_2
no magnetic field

Electron drift **velocity**

- Triple-GEM technology
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- **High rate TB @ MAMI - Mainz**





- Triple-GEM can measure the drift velocity of the electron from:
  - The time distribution of all the signals
  - The width of the gap (5mm)
- **Drift velocity** = drift gap / (leading time – rising time)
- The drift velocity changes at 10^7 Hz/cm^2, here seems that the electrons slow down

* **Time distribution**
30° angled tracks
5 mm conversion gap
820V on the GEMs
Ar:CO_2
no magnetic field

** **Drift velocity**
30° angle track
5 mm drift gap
~ 10k gain
both gas mixtures
no magnetic field

Conclusion

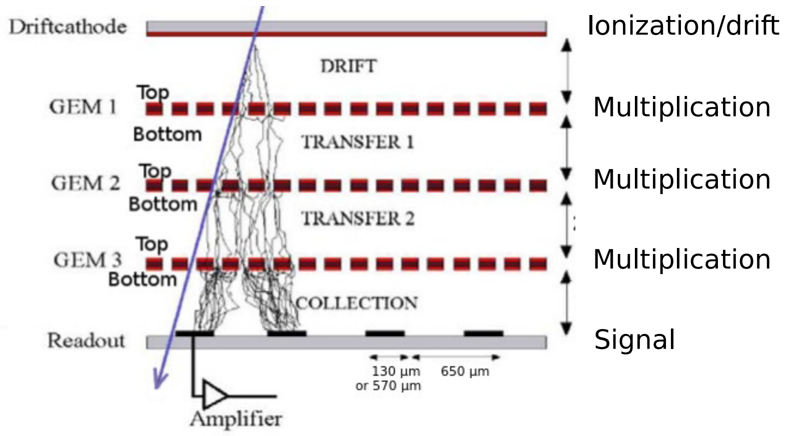
- Several TBs at H4-CERN and MAMI-Mainz have been performed to study the performances of the triple-GEM
- **Two reconstruction algorithm** use the charge and time information to measure the track position
- **Magnetic field** introduce a preferential direction of the electron drift but the use of a combination of the two algorithms keep the **spatial resolution stable** in a wide angular range
- Triple-GEM shows a stability to higher beam rate with respect other technology but a rate of **10^7 Hz/cm^2** are the limits for a stable reconstruction of the µTPC

Thanks

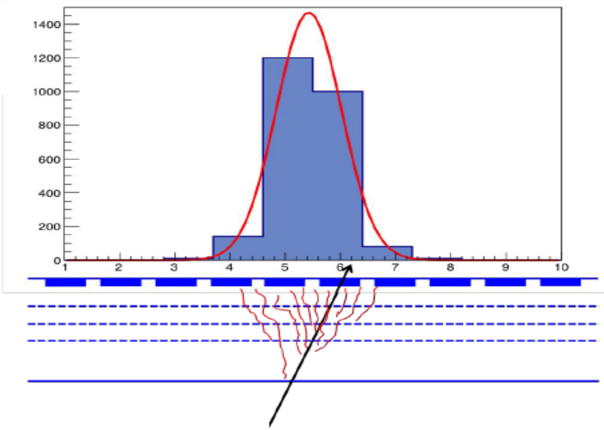
Backup

The GEM technology

- **Triple-GEM technology**
- Position reconstruction methods
- Magnetic field TB @ H4 - CERN
- High rate TB @ MAMI - Mainz



Charge distribution @ anode



Diffusion

- *Due to:* the **gas mixture**
- *Effect:* enlarged charge distribution

Lorentz force

- *Due to:* the **magnetic field** perpendicular to the e- direction of motion
- *Effect:* enlarged charged distribution, far from the Gaussian shape

Merge: the idea

- The **mean cluster** size **has a minimum** in the focusing configuration and due to geometrical reasons **it increases** as the angle deviates from this configuration

- The idea is to assign **weights** to the CC and the µTPC and to **average** the two measurements

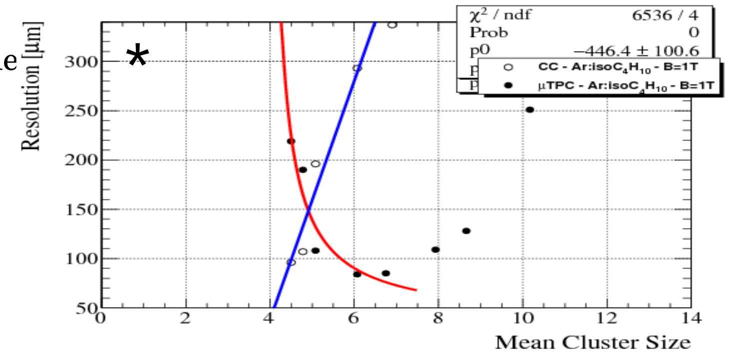
$$x_{merge} = \frac{x_{cc} \cdot w_{cc} + x_{tpc} \cdot w_{tpc}}{w_{cc} + w_{tpc}}$$

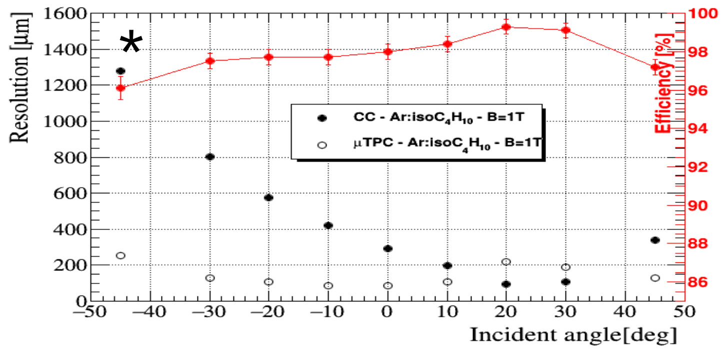
- As **Atlas** suggests, it is possible to use the cluster size to determine the weights of the merge:

$$w_{tpc} = (N_{hit}/N_{cut})^2$$

$$w_{cc} = (N_{cut}/N_{hit})^2$$

- Looking at the CC and µTPC resolution as a function of the cluster size it seems that $w_{cc} \sim N_{cut}$ and $w_{tpc} \sim (1/N_{cut})$

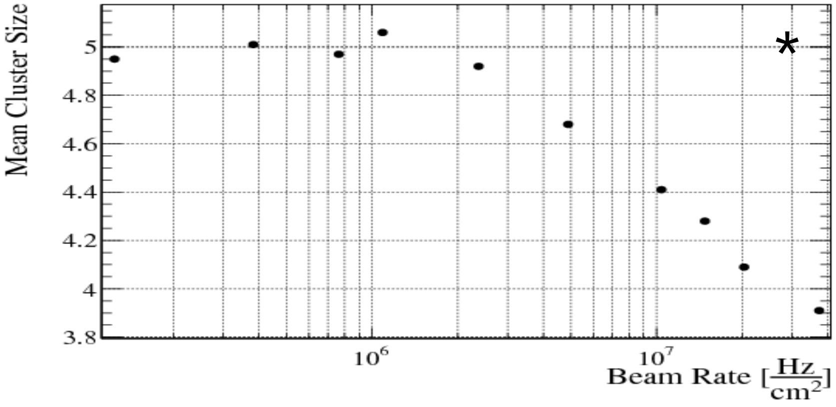


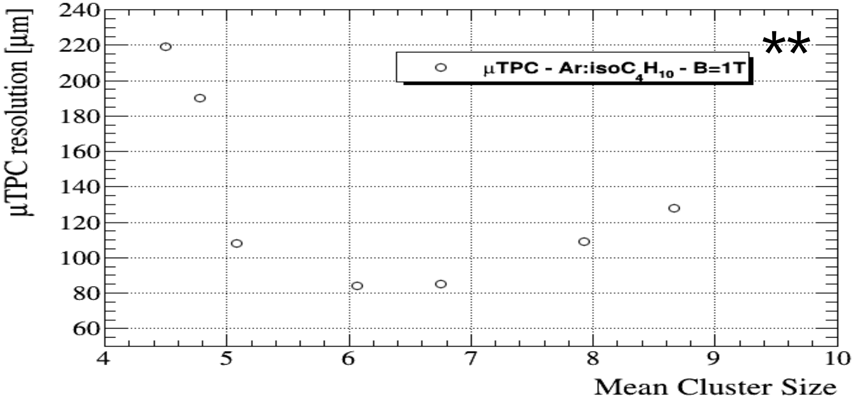


* **Angle scan**
5 mm conversion gap
820V on the GEMs
$Ar:iC_4H_{10}$
1.5 kV/cm drift field
1 T magnetic field

High rate test @ MAMI: # of Strip cluster size

- The mean cluster size remains stable up to 10^6 Hz/cm^2
- The expected resolution for the µTPC for this configuration stays around 100 µm but it degrades as the cluster size is reduced

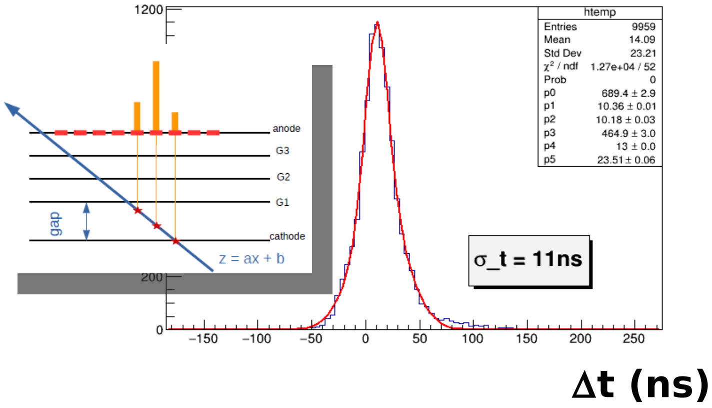


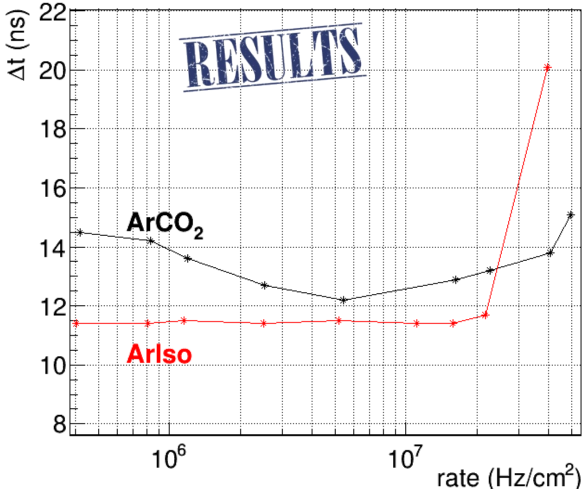


* **Beam profile**
30° angle track
820V on the GEMs
Ar:iC_4H_{10}
2 kV/cm drift field
no magnetic field

** **Angle scan data**
orthogonal track
820V on the GEMs
Ar:iC_4H_{10}
1.5 kV/cm drift field
1 T magnetic field

High rate test @ MAMI: Time resolution





Evaluation

Δt = t2 – t1 distribution

All contributions

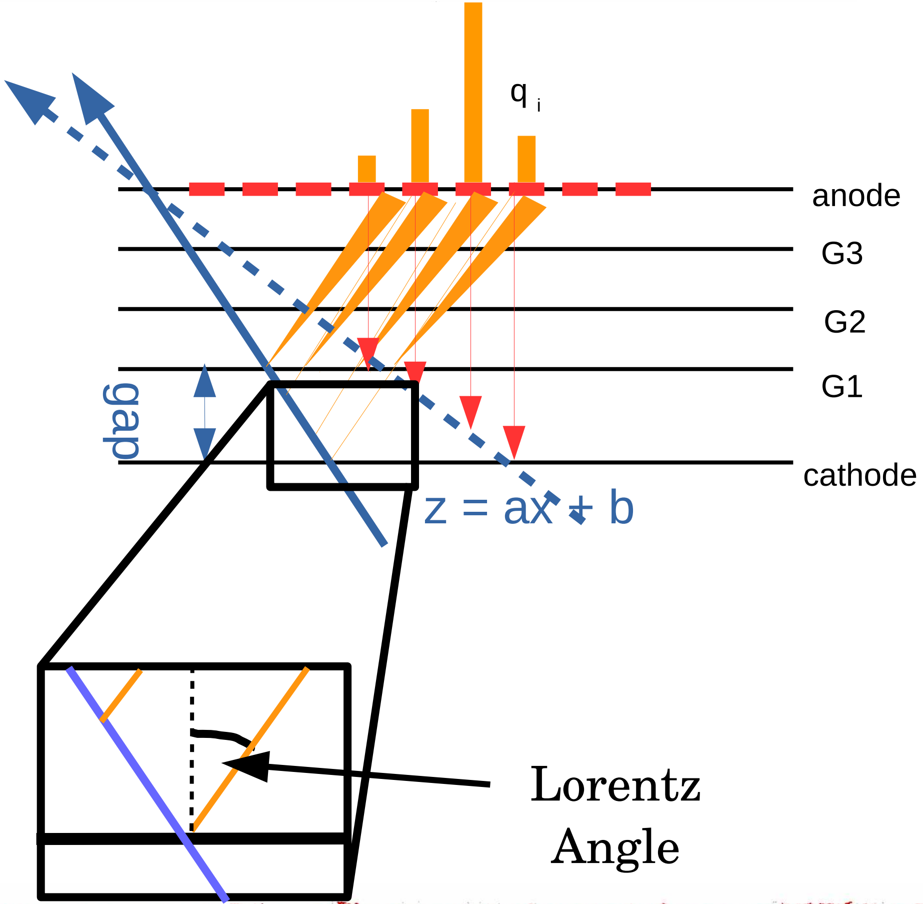
- Detector resolution
- APV-25 jitter contribution

Time resolution = 8.4 ns

The time resolution starts worsening after 10^7 Hz/cm²

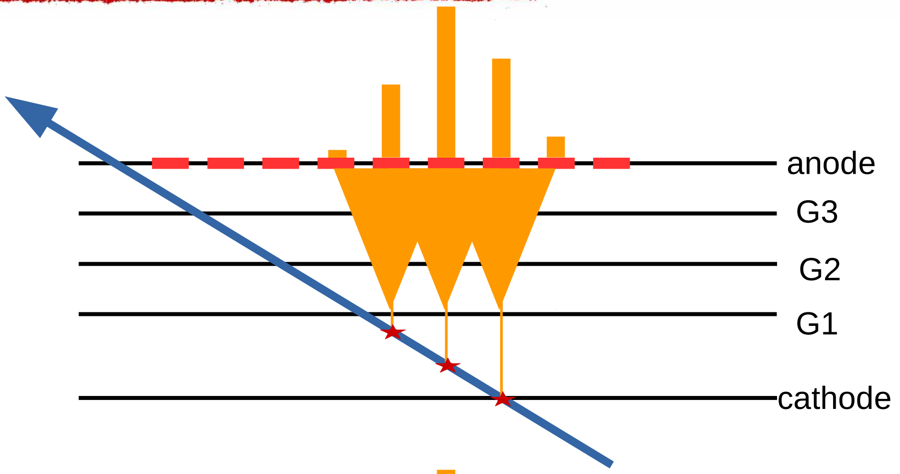
Reconstruction Technique: µTPC in B

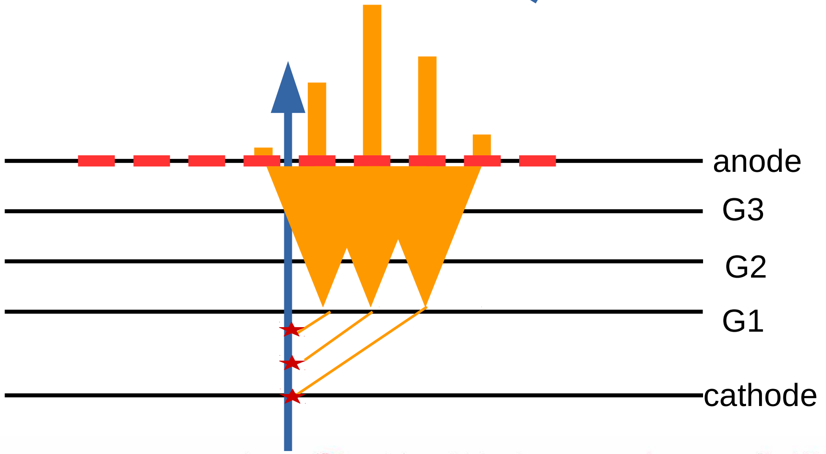
- The magnetic field has to taken into account for the µTPC reconstruction
- The parameter that describe this effect is the Lorentz angle
- A shift of the µTPC points has to be performed and this changes the reconstruction from the dashed line to the continuum one



Analysis results CC: Angled tracks and B effect

- Each primary electron that reaches the first GEM creates an avalanche with a Gaussian distribution
- If the track is not orthogonal then the primary reaches the first GEM in different place
- Even better, if the track path is different from the electron drifting direction then the primary reaches the first GEM in different place
- The charge distribution at the anode is no more Gaussian and the performances of the charge centroid degrade





Analysis results CC: Angled tracks and B effect

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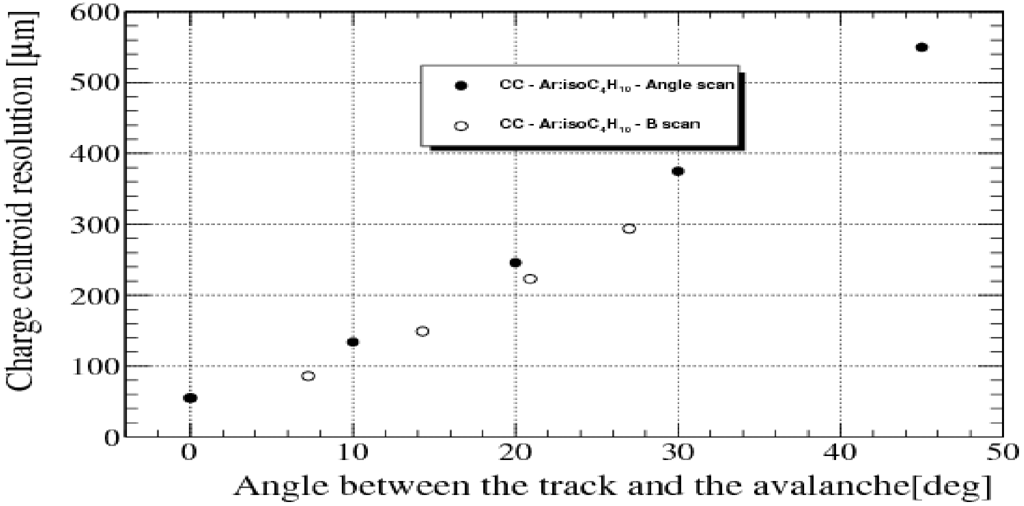
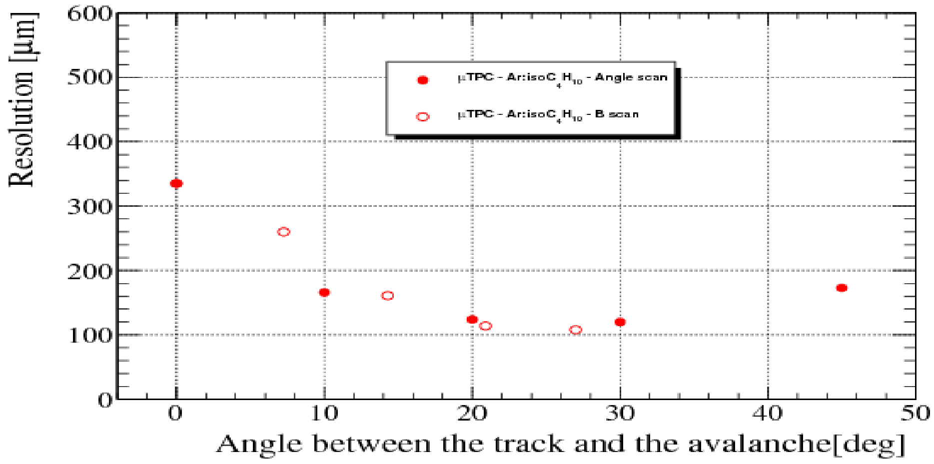
- **The charge distribution at the anode is no more Gaussian and the performances of the charge centroid degrade**
- Magnetic field scan points are showed as function of the Lorentz angle



Analysis results µTPC: Angled tracks and B effect

- Each primary electron that reaches the first GEM creates an avalanche with a Gaussian distribution
- If the track is not orthogonal then the primary reaches the first GEM in different place
- Even better, if the track path is different from the electron drifting direction then the primary reaches the first GEM in different place
- **The cluster size increases and the µTPC improves its performance**
- Magnetic field scan points are showed as function of the Lorentz angle



Analysis results: Summary plot

- Charge centroid and μTPC show an anti-correlated behavior
- Incident angle ans Lorentz angle play the same role on the performances of the detector