New Readout Codification in Large-Area Multi-Gap Timing RPCs for Muon Scattering Tomography

João Pedro Saraiva

Laboratory of Instrumentation and Experimental Particle Physics

LIP Coimbra – Portugal

Santiago de Compostela - September 9–13, 2024

joao.saraiva@coimbra.lip.pt

Outline

Background

RPCs are well suited for large-area applications, since:

- they can be built at relatively low cost
- cover large surfaces with high efficiency, spatial and time resolutions

Background

RPCs are well suited for large-area applications, since:

- they can be built at relatively low cost
- cover large surfaces with high efficiency, spatial and time resolutions

Driving cost of the detector:

- Front-End Electronics and related electronics

Background

RPCs are well suited for large-area applications, since:

- they can be built at relatively low cost
- cover large surfaces with high efficiency, spatial and time resolutions

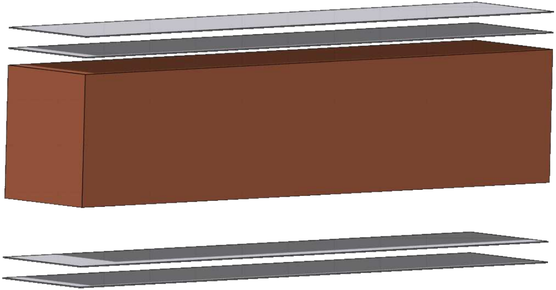
Driving cost of the detector:

- Front-End Electronics and related electronics

For **very large areas** with **submillimetric spatial resolution**, the **number of FEE channels** can reach prohibitive values due to cost constraints

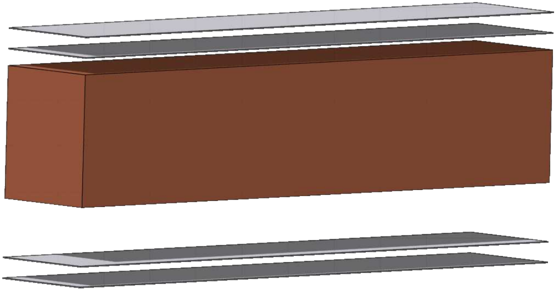
Background

For instance, the **Muon Scattering Tomography (MST)** of a shipping container requires a sensitive area $\sim$130 m^2



Background

For instance, the **Muon Scattering Tomography (MST)** of a shipping container requires a sensitive area ∼130 m^2



with submillimetric spatial resolution ⇒ **25000+ FEE chs**

(assumed pitch: 2.54mm)

Objective

Develop a new readout technique with primary aim of:

- decoupling **number of FEE channels** & **RPC sensitive area**.

Objective

Develop a new readout technique with primary aim of:

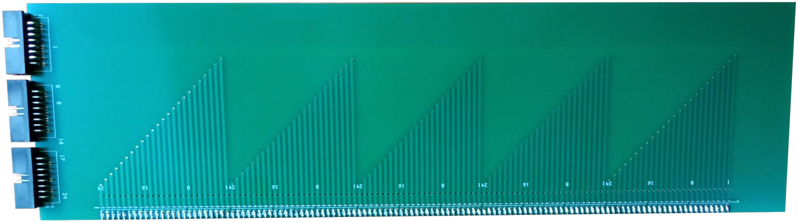
- decoupling **number of FEE channels** & **RPC sensitive area**.

Keeping:

- high spatial resolution $\rightsquigarrow$ $<$ **1 mm** σ
- very good time resolution $\rightsquigarrow$ $<$ **100 ps** σ

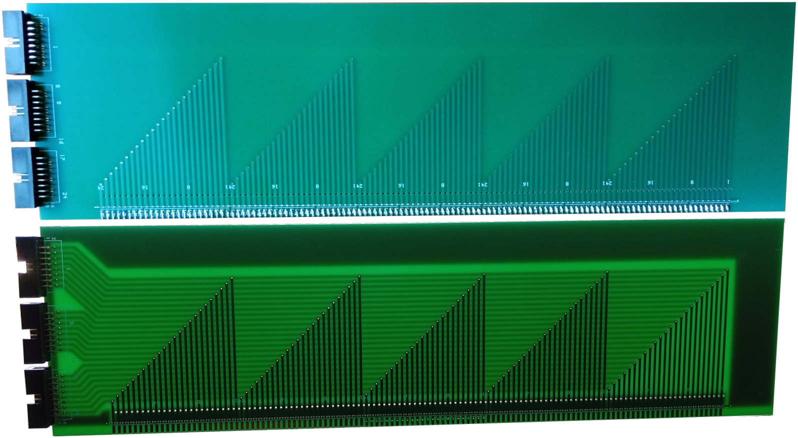
Novel Readout PCB

Signal Merging PCB (SMPCB)



Novel Readout PCB

Signal Merging PCB (SMPCB)



5 strips connected in parallel × 24 chs

SMPCB + Thin-Strip Readout PCB

24 FEE channels $\Longrightarrow$

SMPCB + Thin-Strip Readout PCB

24 FEE channels $\Longrightarrow$

120 strips $\Longrightarrow$

SMPCB + Thin-Strip Readout PCB

24 FEE channels ⟹

120 strips ⟹

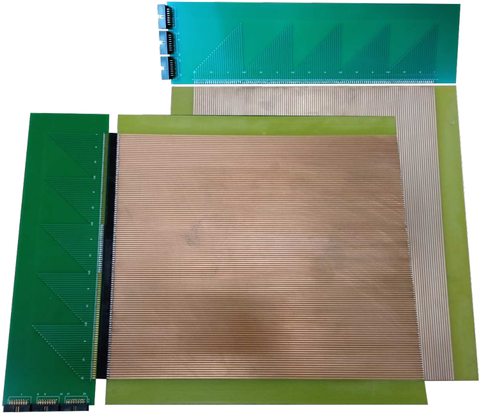
	Thin Strips
Length [mm]	360
Width [mm]	303.8
Strip number	120
Pitch [mm]	2.54
Interstrip [mm]	1
FEE type	charge-sensing amplifiers
Measured quantity	charge
Extracted quantity	1D fine position

SMPCB + Thin-Strip Readout PCB

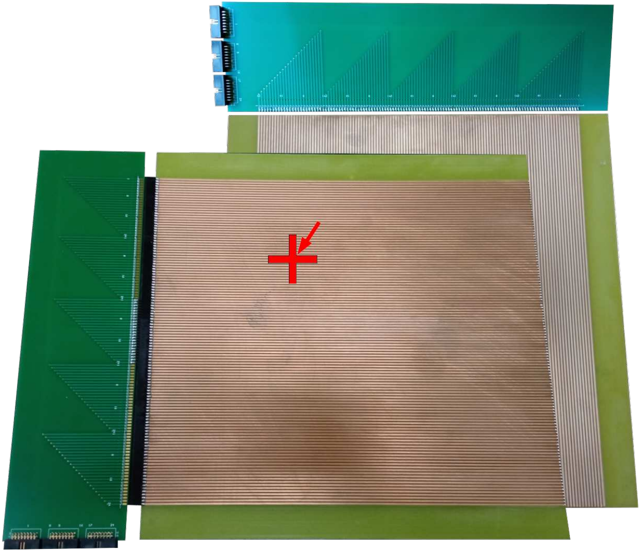
24+24 FEE channels

120+120 strips

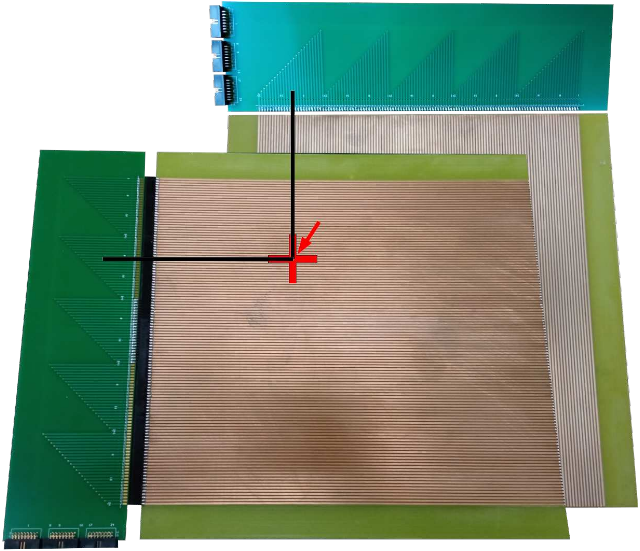
2D submillimeter-precision measurements of ionizing particles



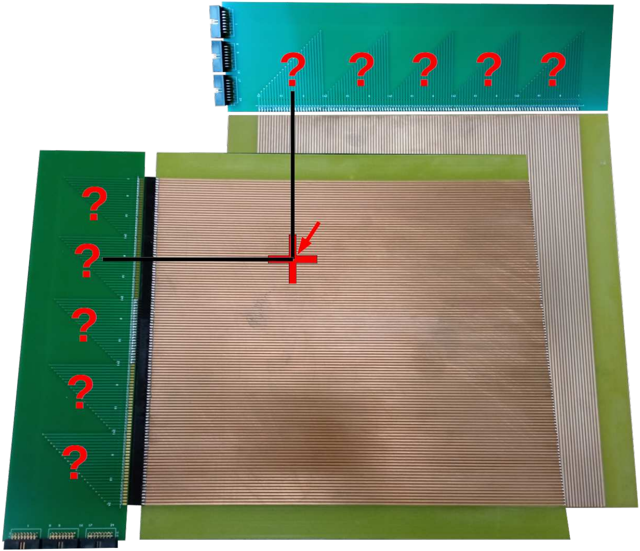
Particle hit - I



Particle hit - II

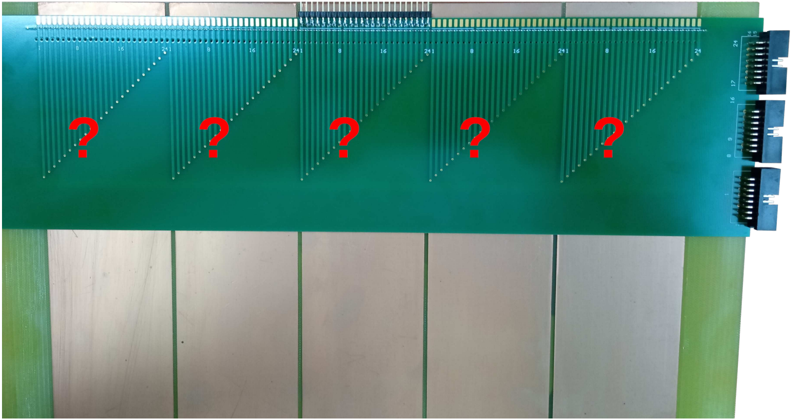


Particle hit - III



Wide-Strip Readout PCB

The ambiguity raised by grouping together the thin strips must be disentangled in order to determine in which group the signal was in fact induced



Particle hit - IV

The wide-strip readout electrode provides an additional 2D raw position of each event, allowing the impinged group to be identified in both directions

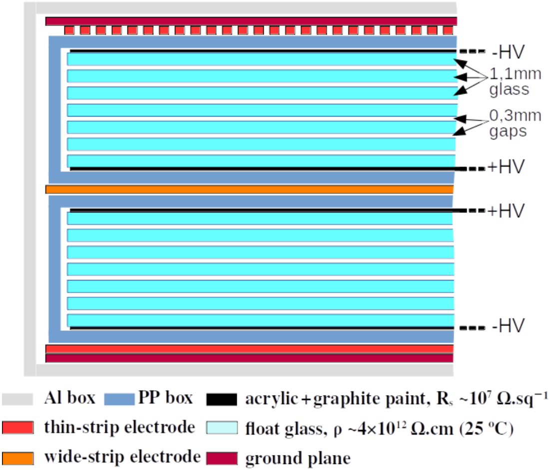
Wide-Strip Readout PCB - II

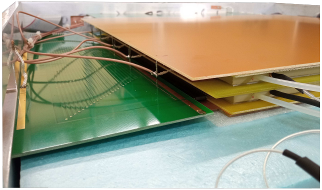
5 FEE channels ⟹

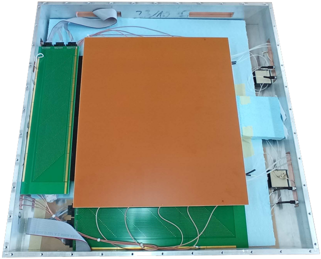
	Wide Strips
Length [mm]	380
Width [mm]	303
Strip number	5
Pitch [mm]	61.0
Interstrip [mm]	2
FEE type	current-sensing amplifiers
Measured quantity	charge, time
Extracted quantity	2D course position, event time

Layer Diagram & Full Setup

Stack of 2 tRPCs with active area of 30×30 cm^2







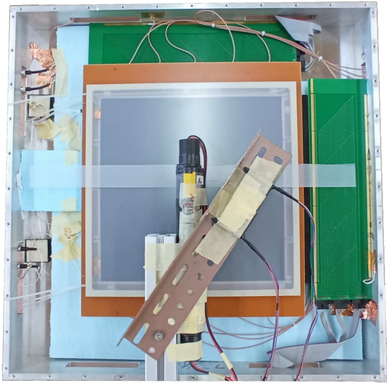
Detector operated during weeks with cosmic rays

- Open gas flow, with **R-134a (95.5%)** and **SF6 (4.5%)**
- Reduced field set to ∼**380 Td** (∼2.75 kV/gap, 92 kV/cm)

Coincidence Trigger

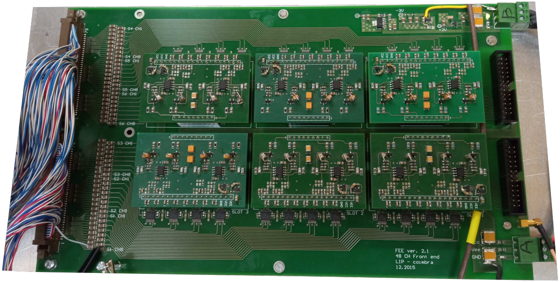
generated externally by plastic scintillators above and below the RPCs:

- $8\times4\times1\ cm^3$ coupled to SiPMs
- $8\times2\times3\ cm^3$ coupled to PMTs



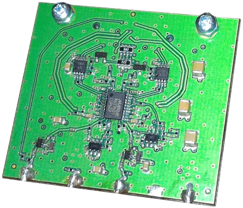
2D fine position

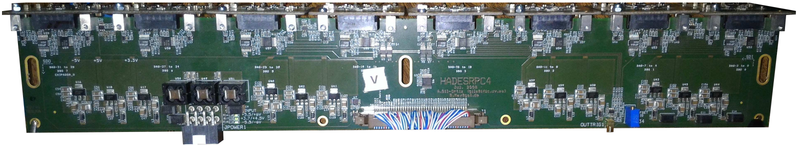
- Charge integrating FEE (custom-designed)
  - 2×24 chs
- Integration of the fast and slow components of the induced signals
- Pulses digitally processed after digitization (trapezoidal filter)
- $\mathbf{X}_{fine}$, $\mathbf{Y}_{fine}$ via charge interpolation



2D raw position + time

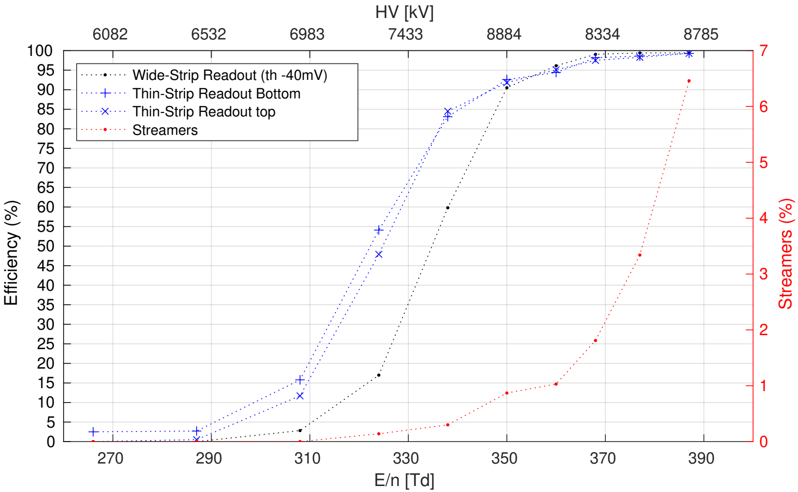
- fast FEE (HADES @ GSI Darmstadt)
    - ∗ 2×5 chs (both ends of 5 wide strips)
- $\mathbf{T} = (T_f + T_b)/2$ (front (f) & back (b))
- $\mathbf{Y}_{course} = (T_f - T_b)/2$
- **Q** via Time over Threshold method
  (fast component of the induced signals)
- $\mathbf{X}_{course}$ via charge interpolation





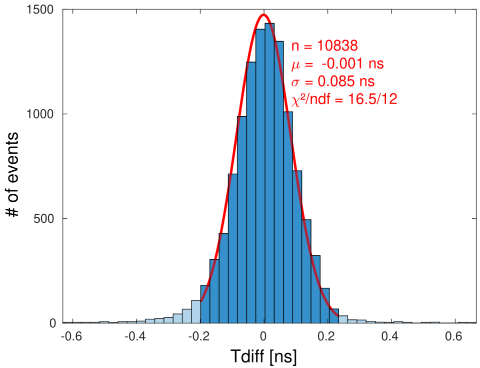
Efficiency & Streamers

Efficiency slightly above 98% and 4% of streamers @ 380 Td



Time Resolution

- **T**$_{RPC}$ **- T**$_{scint.}$
- run of 33 days
- **74 ps** σ after removing scintillator contribution
- corrected for time walk

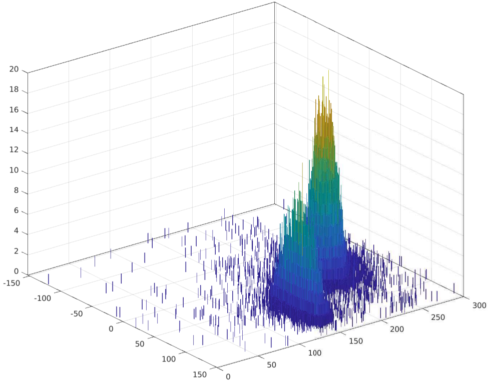


Spatial Resolution

2D position map (projected shadows) of scintillators

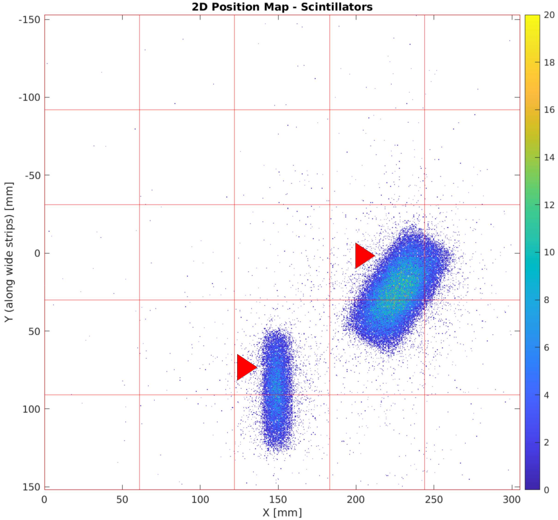
located on both sides of the RPCs

- $8 \times 4 \times 1$ cm^3 scintillators coupled to SiPMs
- $8 \times 2 \times 3$ cm^3 scintillators coupled to PMTs



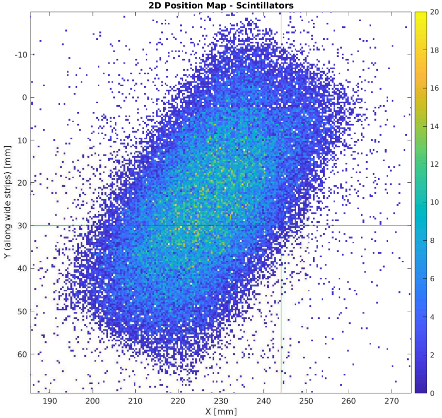
Spatial Resolution

300 µm-diameter spacer lines visible in the position map

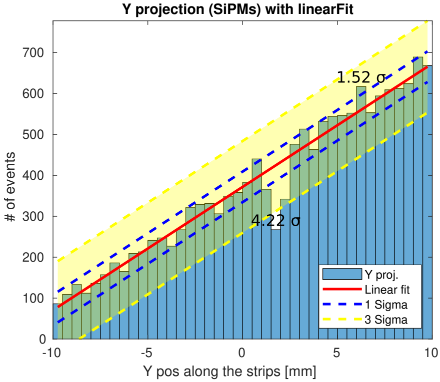


Spatial Resolution - scint. coupled to SiPMs

Significant lack of events near the 300-µm gas gap spacers



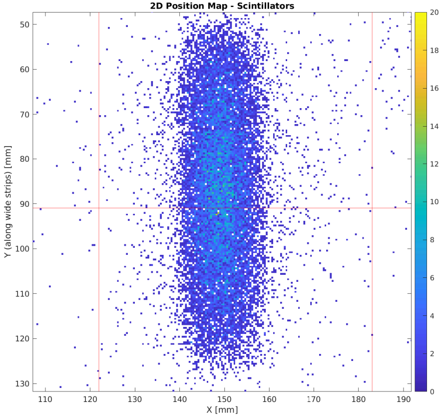
Close-up view of the 2D map



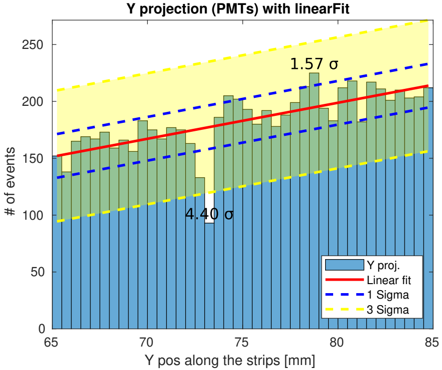
Projection onto the Y-axis

Spatial Resolution - scint. coupled to PMTs

Clear indication of the submillimetric resolution of the RPCs



Close-up view of the 2D map



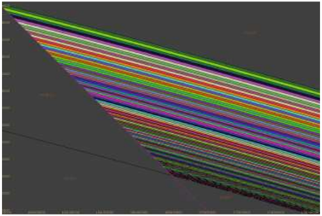
Projection onto the Y-axis

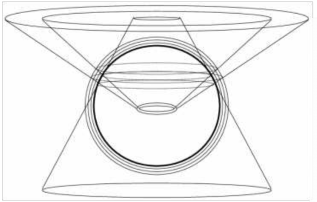
Muon Scattering Tomography (MST)

Application requiring large sensitive area + high spatial resolution

FLUKA 1^{st} step sim.: extract **muon flux at sea level**

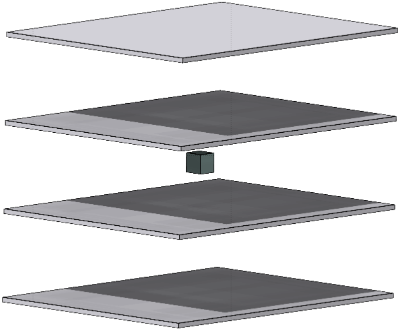
- atmospheric model: 100 layers from 0 to 70 km above sea level with different densities
- scoring between three cones for specific geomagnetic latitude
- Primary spectra, Galactic C. Ray source:
  - Ion flux from Z = 1 to Z = 28 modulated for a minimum solar activity;
  - Energy: from 100MeV to 100TeV;
  - Geographic lat/long: 40.20ºN/8.42ºW;
  - Altitude: 105 m;
  - Vertical cutoff rigidity: 7.5 GeV;
  - Geomagnetic cut-off acceptance: 7 GeV.





MST – Two step simulation

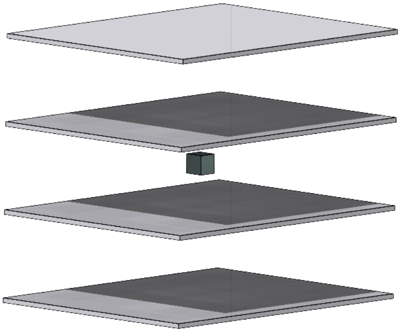
Muon flux at sea leavel (1^{st} step) afterwards used into a planar geometry with 4 RPCs and 10×10×10 cm^3 high-Z material blocks at the center of the detector (2^{nd} step):



FLUKA geometry
Four 1.6×1.2 m^2 RPCs, 45 cm apart

MST – Two step simulation

Muon flux at sea leavel (1^{st} step) afterwards used into a planar geometry with 4 RPCs and 10×10×10 cm^3 high-Z material blocks at the center of the detector (2^{nd} step):



FLUKA geometry
Four 1.6×1.2 m^2 RPCs, 45 cm apart

doi.org/10.1016/j.nima.2023.168183

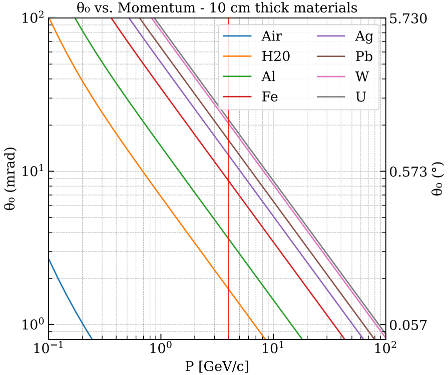
MST – Lynch & Dahl formula

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 ln \left(\frac{x z^2}{X_0 \beta^2} \right) \right] \quad \text{rad}$$

(rms width of the projected angular distribution)

- Angular distribution due to the multiple scatterings follows a gaussian distribution
- 4 GeV muons in 10 cm thick material, Fe: ∼0.5º, W: ∼1º

High spatial resolution needed due to the precision needed to measure the **small scattering angles**

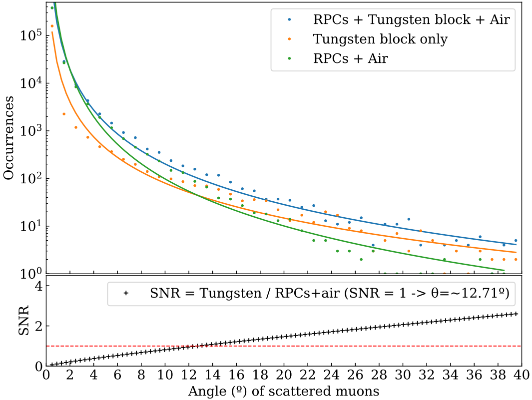


MST - Material Budget - I

Angular distributions from FLUKA simulations of the **scattered muons inside the fiducial region**

Comparing simulations:

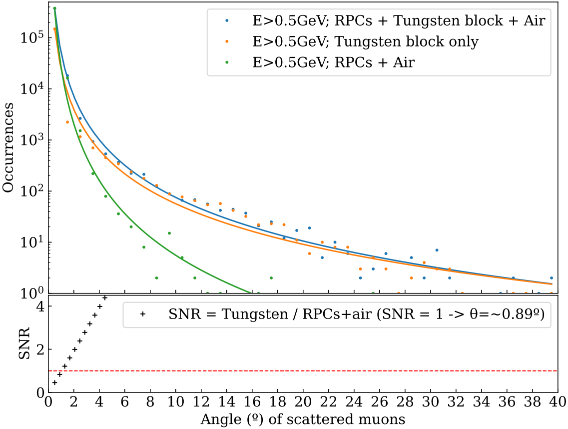
- **full geometry**: **RPCs + Tungsten** block ($10\times10\times10$ cm^3) + **air**
- '**signal**': tungsten block only
- '**noise**': all except tungsten: RPCs + air



Muon scatterings from the tungsten block are dominant above ∼12°

MST - Material Budget - II

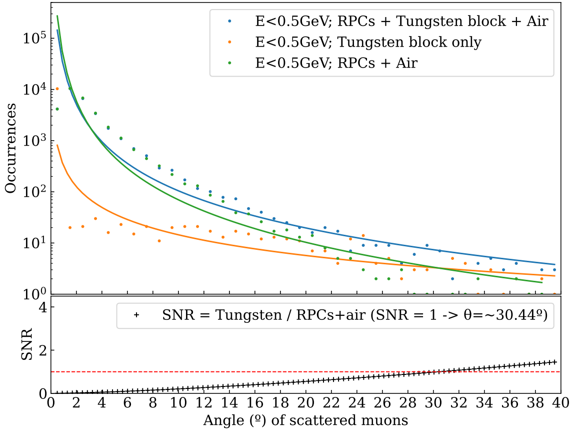
If only muon of high energy: **above 500 MeV**



Muon scatterings from the tungsten block are dominant above ~0.9°

MST - Material Budget - III

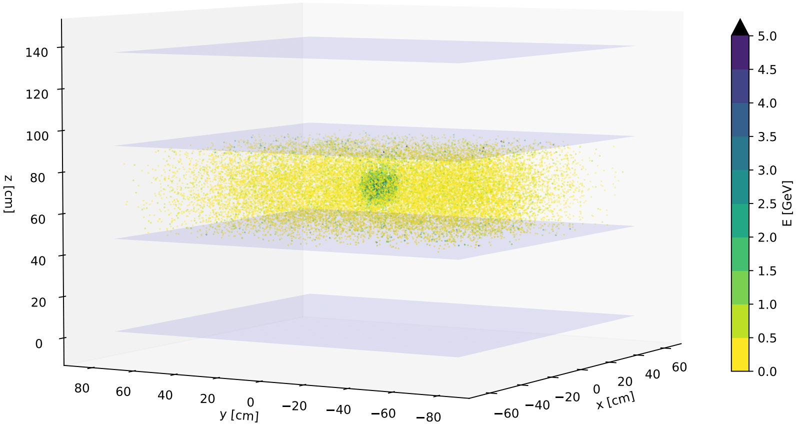
If only muon of low energy: **below 500 MeV**



Muon scatterings from the tungsten block are dominant above ~30°

MST - Material Budget - 3D plot of PoCAs

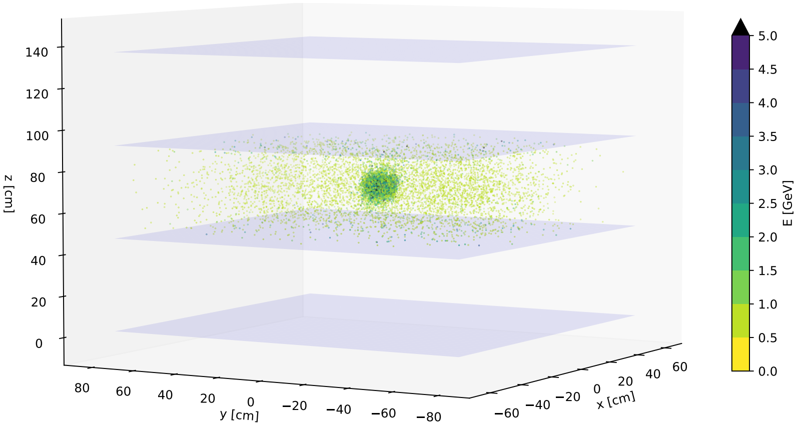
Point of Closest Approach (PoCA) between incident and exiting traj.; applied restrictions: **scatters > 1.5°**



Low energy muons highly affected by the material budget

MST - Material Budget - 3D plot of PoCAs

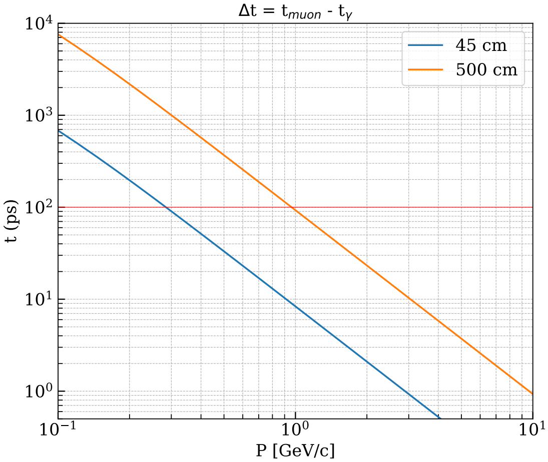
Point of Closest Approach (PoCA) between incident and exiting traj.; applied restrictions: **scatters > 1.5° & E > 500 MeV**



Low energy muons have high scatters even in air ⇒ reject them!

MST - Time of Flight (TOF)

For ~**100 ps** time resolution: **300 MeV/c** muons can be rejected for a fiducial region of 0.45 m (**1 GeV/c** for 5 m)



How long to identify the 10 cm tungsten block?

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**

Applied approach:

- divide the fiducial region into 5×5×5 cm^3 voxels

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**

Applied approach:

- divide the fiducial region into 5×5×5 cm^3 voxels
- populate voxels with POCAs (control run subtracted)

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution $\Rightarrow$ **less than 1 min**

Applied approach:

- divide the fiducial region into $5\times5\times5$ cm^3 voxels
- populate voxels with POCAs (control run subtracted)
- compute the average number of POCAs per voxel (μ)

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**

Applied approach:

- divide the fiducial region into $5{\times}5{\times}5$ cm^3 voxels
- populate voxels with POCAs (control run subtracted)
- compute the average number of POCAs per voxel (μ)
- search for outliers relative to the mean (μ)

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**

Applied approach:

- divide the fiducial region into $5\times5\times5$ cm^3 voxels
- populate voxels with POCAs (control run subtracted)
- compute the average number of POCAs per voxel (μ)
- search for outliers relative to the mean (μ)
- plot the outliers with highest number of POCAs, inside ('good voxel') and outside ('bad voxel') the tungsten block region

How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**

Applied approach:

- divide the fiducial region into 5×5×5 cm^3 voxels
- populate voxels with POCAs (control run subtracted)
- compute the average number of POCAs per voxel (μ)
- search for outliers relative to the mean (μ)
- plot the outliers with highest number of POCAs, inside ('good voxel') and outside ('bad voxel') the tungsten block region
- repeat the procedure for different spatial resolutions (0.3 mm and ∼10 mm $\sigma_{x,y}$)

How long to identify the 10 cm tungsten block?

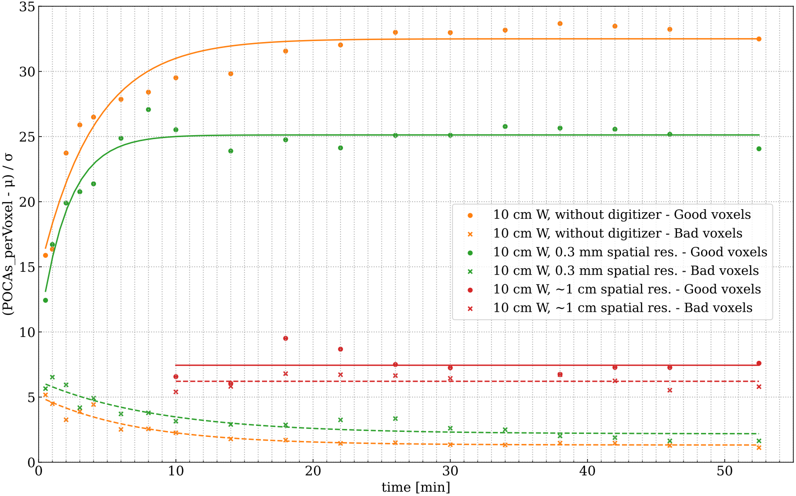
with submillimetric spatial resolution ⇒ **less than 1 min**

Applied approach:

- divide the fiducial region into $5{\times}5{\times}5$ cm^3 voxels
- populate voxels with POCAs (control run subtracted)
- compute the average number of POCAs per voxel (μ)
- search for outliers relative to the mean (μ)
- plot the outliers with highest number of POCAs, inside ('good voxel') and outside ('bad voxel') the tungsten block region
- repeat the procedure for different spatial resolutions (0.3 mm and ∼10 mm $\sigma_{x,y}$)
- decrease the exposure time and repeat all the above!

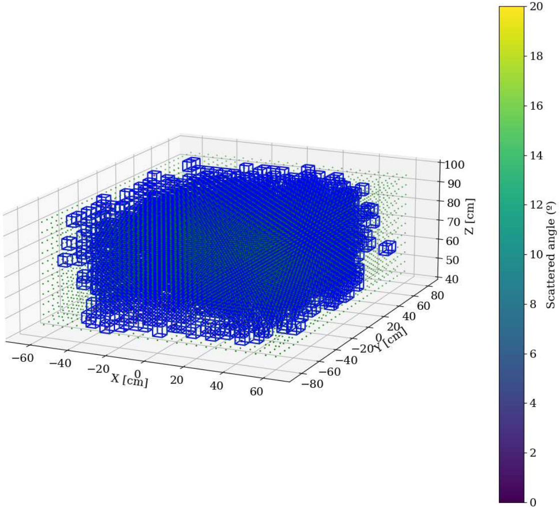
How long to identify the 10 cm tungsten block?

with submillimetric spatial resolution ⇒ **less than 1 min**



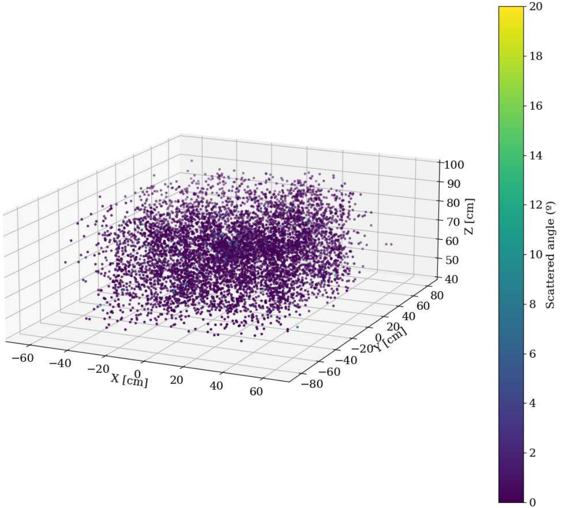
How long to identify the 10 cm tungsten block?

1-min exposure, no digitizer, all POCAs in the fid. reg. + voxels



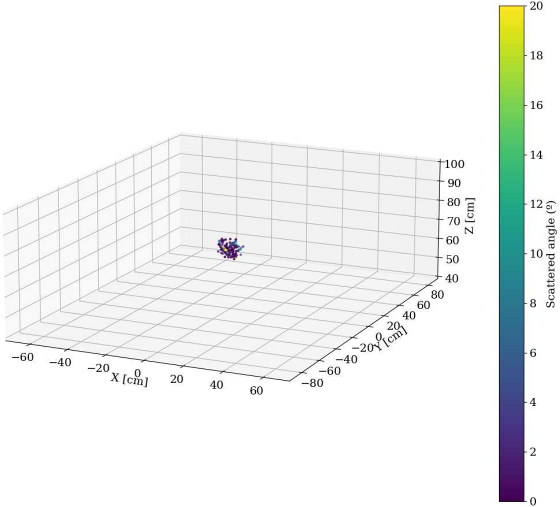
How long to identify the 10 cm tungsten block?

1-min, no digitizer, all POCAs in the fid. reg.



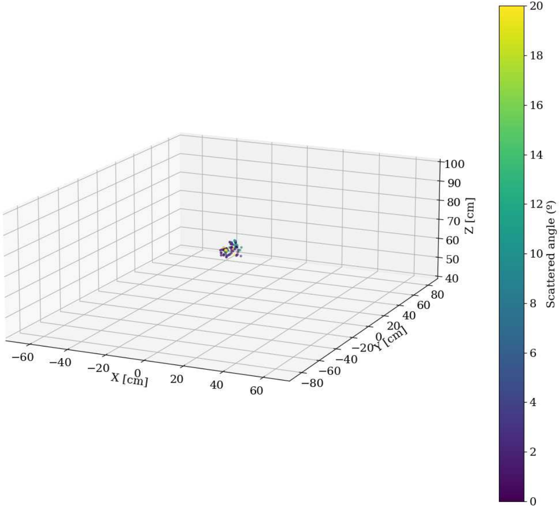
How long to identify the 10 cm tungsten block?

1-min, no digitizer, POCAs 10σ from μ ($\sim$120 events)



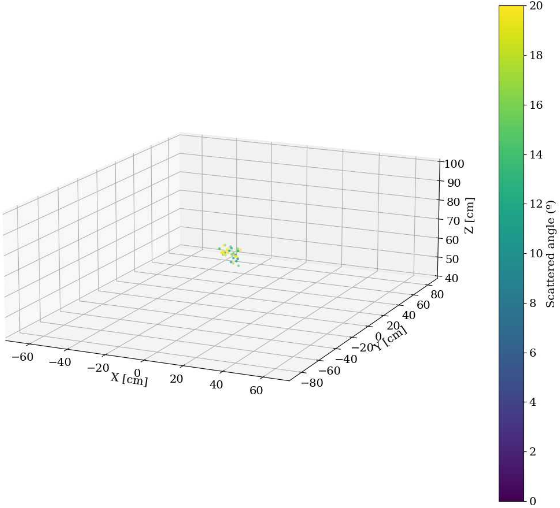
How long to identify the 10 cm tungsten block?

1-min, 0.3 mm spatial res., POCAs 10σ from μ ($\sim$70 events)



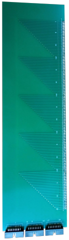
How long to identify the 10 cm tungsten block?

10-mins, 10 mm spatial res., POCAs 6σ from μ ($\sim$33 events)



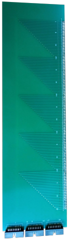
Conclusions

- A new readout PCB was developed to reduce the dependence between the **detector area** and the **number of FEE channels**



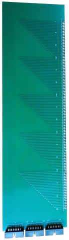
Conclusions

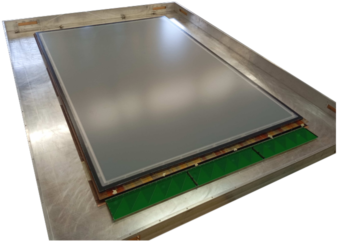
- A new readout PCB was developed to reduce the dependence between the **detector area** and the **number of FEE channels**
- The Signal Merging PCB (SMPCB) was tested with a $\mathbf{30{\times}30\ cm^2}$ multi-gap timing RPC, reducing the number of FEE channels by a **factor of 5**



Conclusions

- A new readout PCB was developed to reduce the dependence between the **detector area** and the **number of FEE channels**
- The Signal Merging PCB (SMPCB) was tested with a **30×30 cm^2** multi-gap timing RPC, reducing the number of FEE channels by a **factor of 5**
- The same 24 channel SMPCB is now being tested with a large scale RPC: **130×90 cm^2** (reduction of FEE chs from ~**866 to 2×24**!)



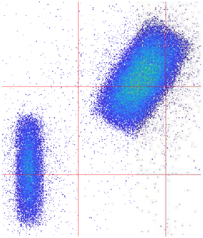


Conclusions

- An additional pick-up electrode with wide strips must be used to resolve the ambiguity introduced by the SMPCB and to provide the time of the events

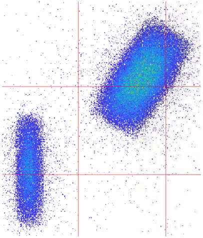
Conclusions

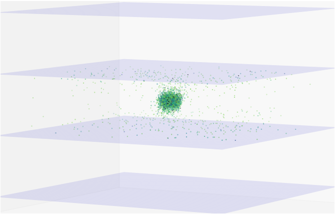
- An additional pick-up electrode with wide strips must be used to resolve the ambiguity introduced by the SMPCB and to provide the time of the events
- 2D high spatial resolution achieved (< **1 mm**) along with a time precision of **74 ps** and efficiency above 98%

Conclusions

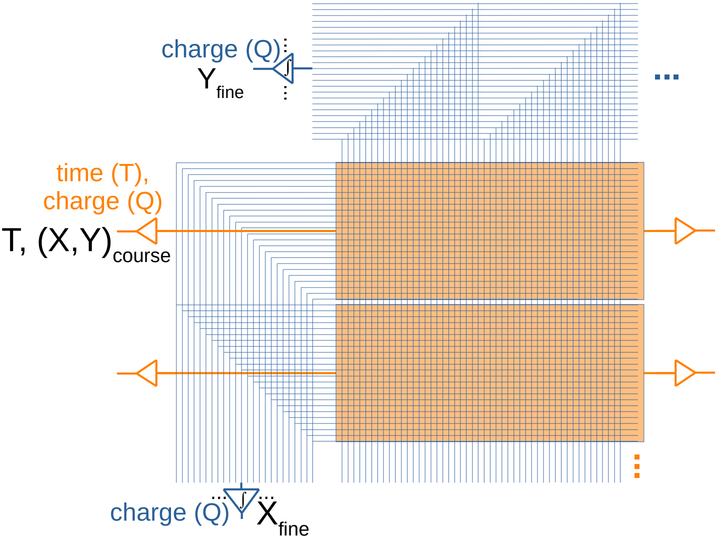
- An additional pick-up electrode with wide strips must be used to resolve the ambiguity introduced by the SMPCB and to provide the time of the events
- 2D high spatial resolution achieved ($< \mathbf{1\ mm}$) along with a time precision of **74 ps** and efficiency above 98%
- Suitable application: **Muon Scattering Tomography** since it requires (1) **large detector areas**, (2) **high spatial resolution** for material discrimination and (3) **high time resolution** to reject low energy muons





Backup

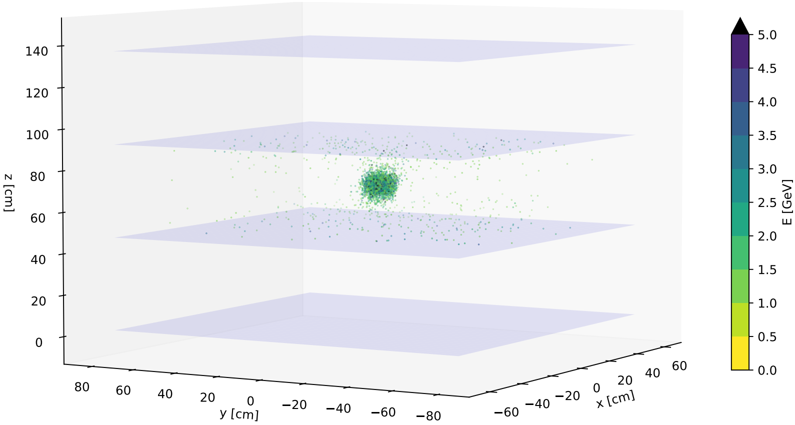
SMPCB + Thin & Wide-Strip Readout PCBs



MST - Material Budget - 3D plot of PoCAs

Point of Closest Approach (PoCA) algorithm; applied restrictions:

scatters above 1.5° & $\mathbf{E}_{muons} > \mathbf{1}$ GeV

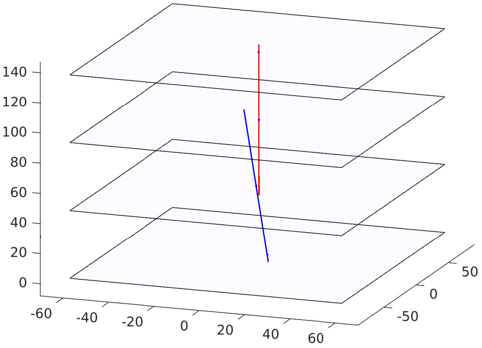


Low energy muons highly affected by the material budget

MST - Spatial Resolution - I

Comparison of angular distributions from generated random numbers following gaussian distributions:

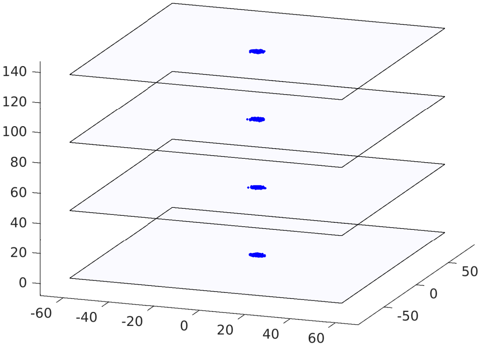
- 4 gaussian distributions, one on each plane, 45 cm apart;
- distribitions vertically aligned;
- two spatial resolutions tested: 1 cm vs. 1 mm (σ_x & σ_y);
- plot angular distributions between incident and exit trajectories.



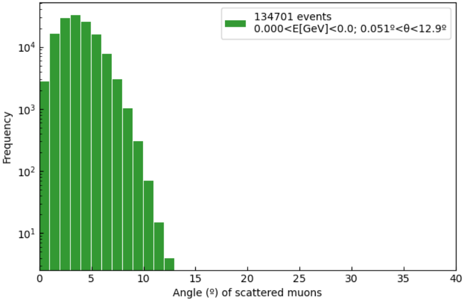
MST - Spatial Resolution - I

Comparison of angular distributions from generated random numbers following gaussian distributions:

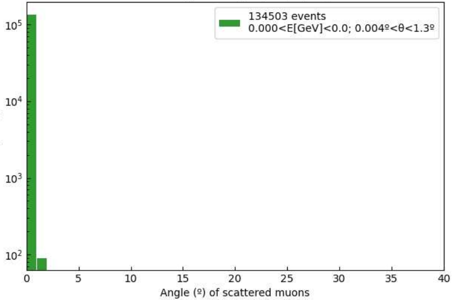
- 4 gaussian distributions, one on each plane, 45 cm apart;
- distribitions vertically aligned;
- two spatial resolutions tested: 1 cm vs. 1 mm (σ_x & σ_y);
- plot angular distributions between incident and exit trajectories.



MST - Spatial Resolution - II



$\sigma_x = \sigma_y = 1$ cm

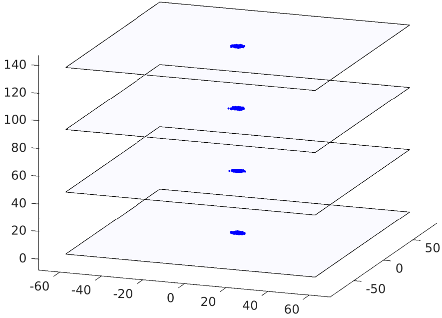


$\sigma_x = \sigma_y = 1$ mm

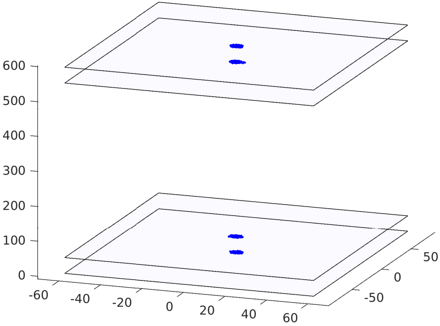
Vertical trajectories with scattered angles up to 12º in case of detectors with a spatial resolution of 1 cm (σ); significant improvement in case of detectors with millimetric resolution.

MST - Spatial Resolution - III

These two geometries result in the same angular distribution:



Fiducial region of 45 cm



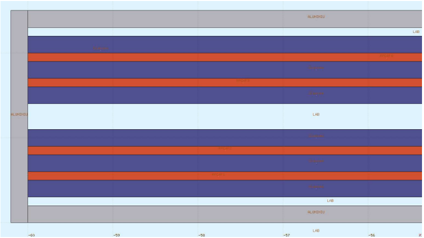
Fiducial region of 5 m

The angular distribution improves increasing the distance between detectors above and below the fiducial region, but not increasing the fiducial region!

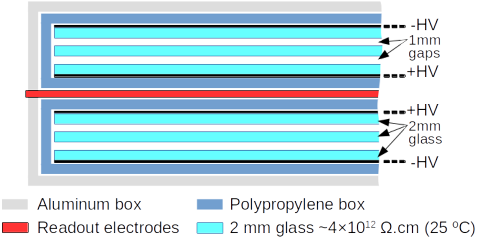
(side effect: reduced detector acceptance)

MST – Detailed Detector geometry

Stack of 2 MRPCs with 2 gas gaps each:



Detailed view of one detector



Layer diagram

Acknowledgment

Work supported by:

- Foundation for Science and Technology (Portugal) (CERN/FIS-INS/0006/2021)
- European Union's Horizon 2020 Research and Innovation programme under Grant Agreement AIDAinnova n.° 101004761