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Muon Spin Spectroscopy with Vertex Reconstruction

ICANS XXIV – 30 October 2023

Outline

- Muon Spin Rotation / Relaxation (µSR) technique
  - Current limitations
- Overcoming current µSR limitations
  - Rate limitation
  - Sample size limitation
- Si-Pixel detectors for µSR to break limitations
- Recent results
  - Lateral resolution
  - First µSR with Si-Pixel detectors

What do we use μSR for?

- Muons are implanted, not scattered, and they interact with the local magnetic fields that they eperience.

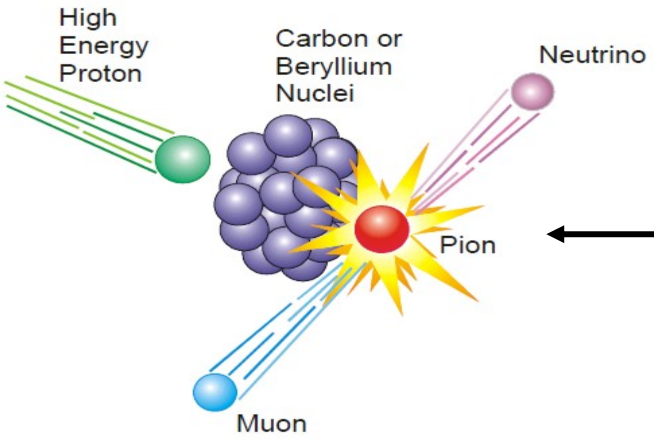
- Muons are local magnetic probe. It allows determination of magnetic / superconducting / other volume fraction.

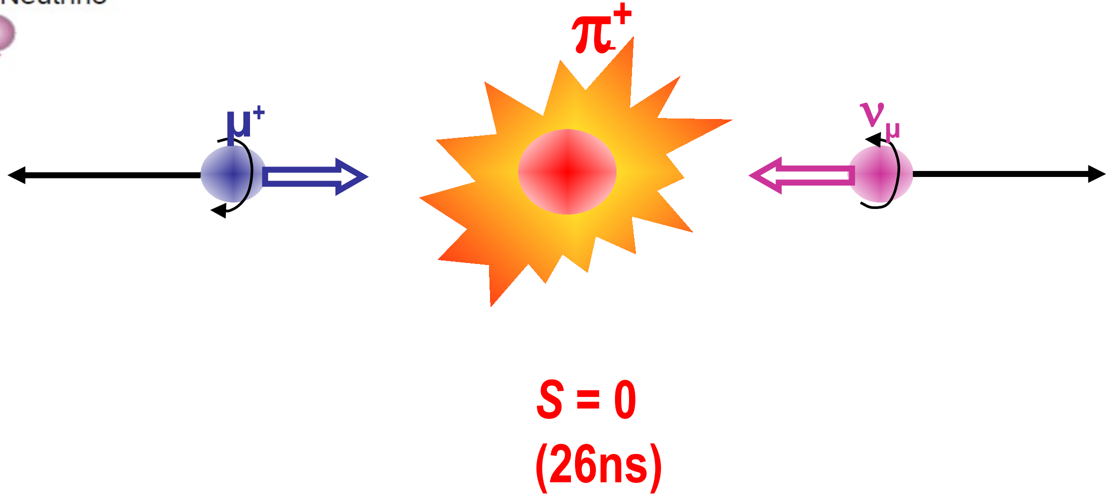
- μSR can be performed at any temperature and/or magnetic field in any sample (solid, liquid or gas).

- Muons are highly sensitive, can detect magnetic fields from moments as small as 10^{-3}–10^{-4} μ_B, and magnetic fluctuations in the range 10^5–10^9 Hz.

- The muon can also act as a hydrogen-like isotope, to study energy materials and semiconducting devices.

Production of Muon

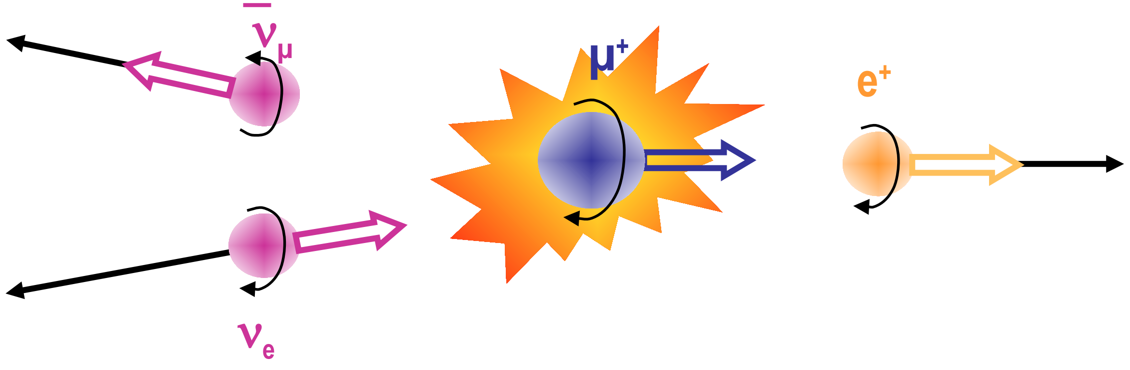




Two-body decay ▶ muon has always the energy 4.1 MeV in the reference frame of the pion (assuming $m_\nu = 0$)

Spin pion = 0 ▶ muon has a **spin 1/2 and is 100% polarized** (since only left-handed neutrinos exist)

β-Decay of the Muon

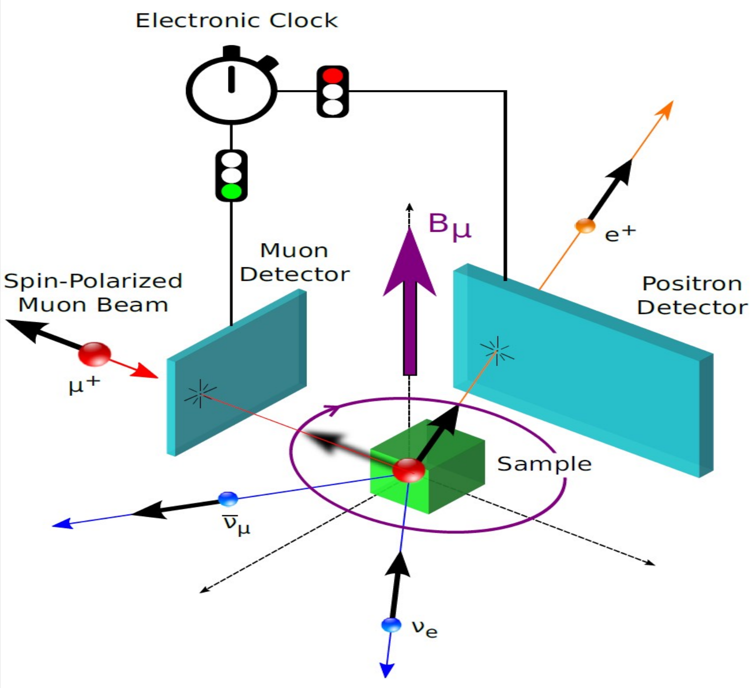


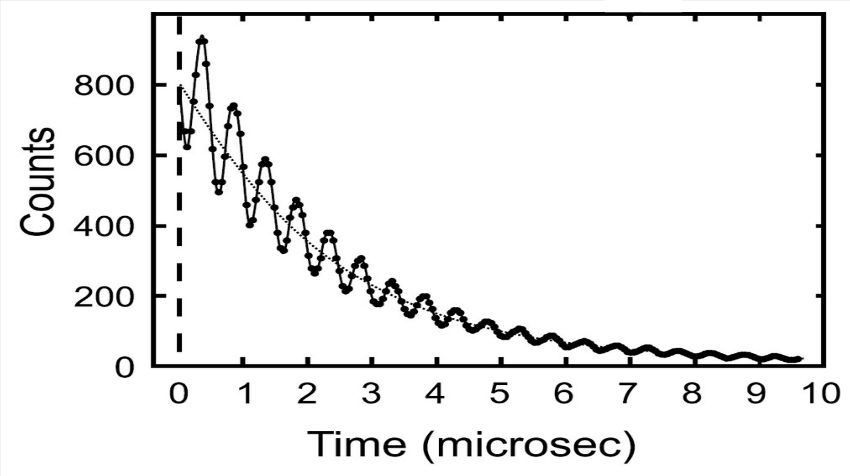
S=1/2
lifetime 2.2 μs

Three-body decay ▶ Distribution of positrons energies

Weak-decay of muon ▶ Parity-violation leading to **positrons emitted preferentially along spin direction.**

The μSR Technique

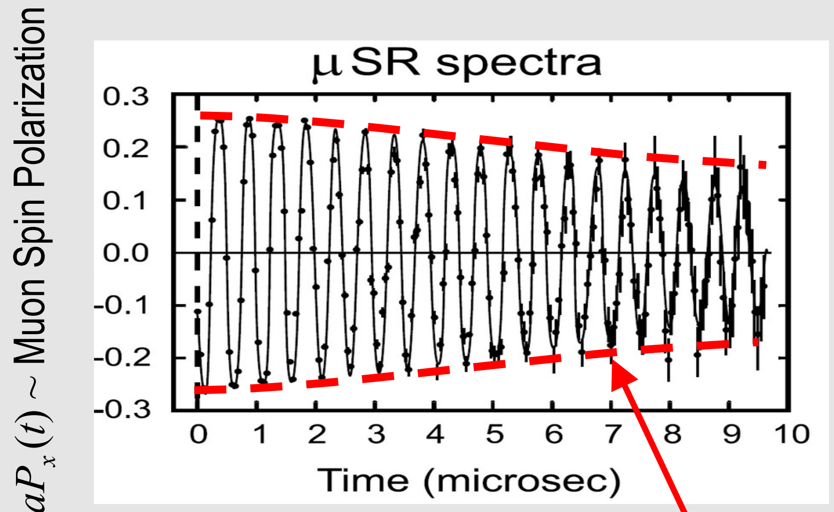


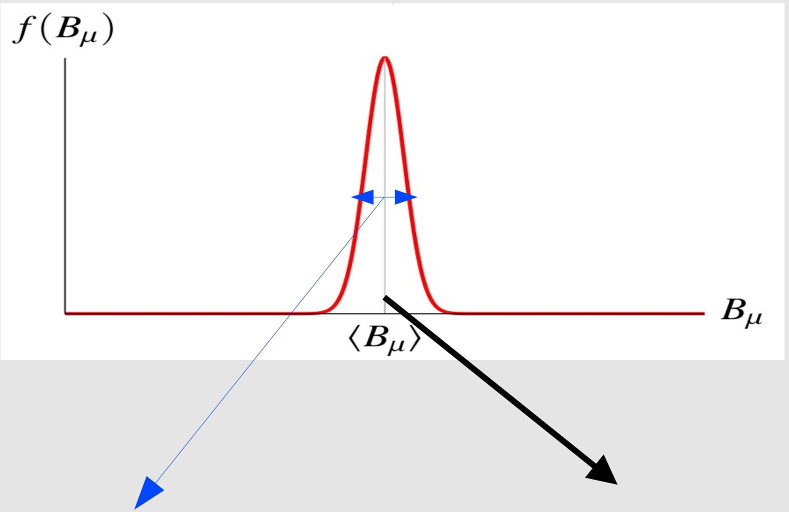


$$N(t) = Bkg + N_0 \exp(-t/\tau_\mu)[1 + a\,\hat{\boldsymbol{n}} \cdot P(t)]$$

$\hat{\boldsymbol{n}}$ - direction of detector

μSR Spectra





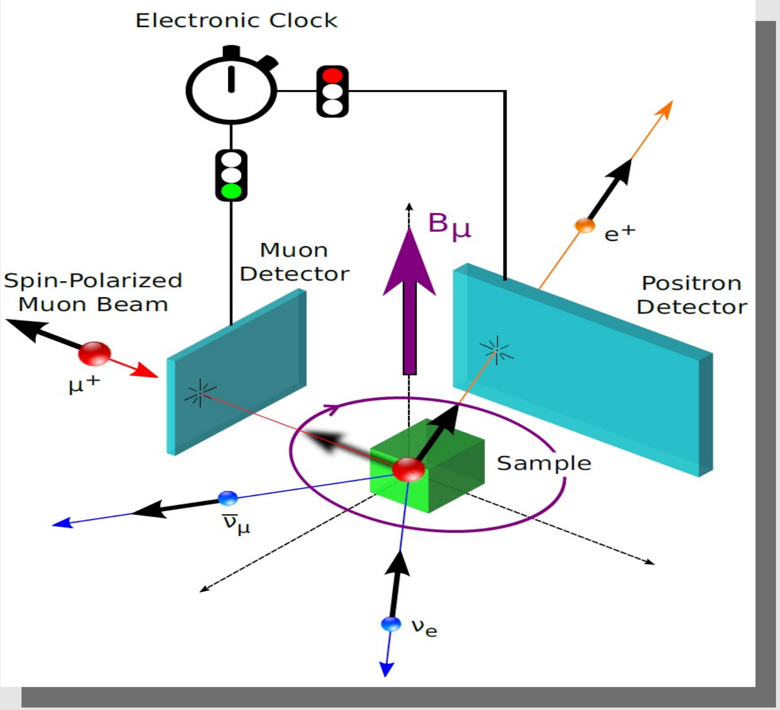
$$N(t) = Bkg + N_0 \exp(-t/\tau_\mu)[1 + a\,\hat{\boldsymbol{n}} \cdot P(t)]$$

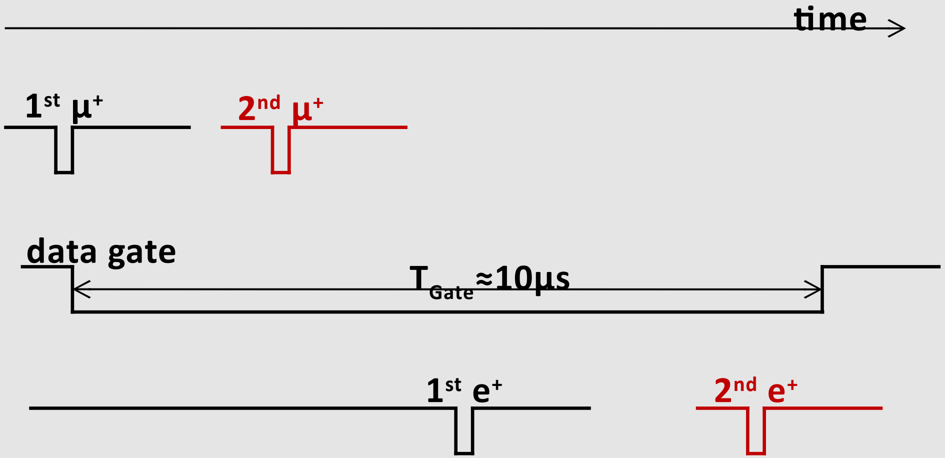
Damping or dynamics

Frequency / γ_μ

Current Rate of Muon at a Typical μSR Spectrometer at PSI

Rate Limitation on μSR at PSI



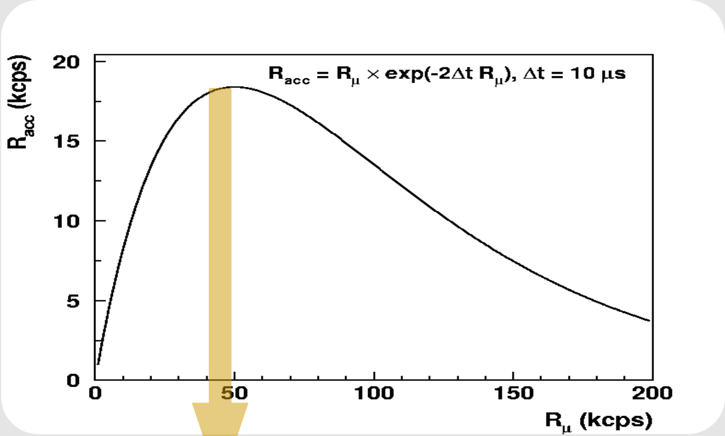


- 1^{st} μ^+: there was **no** other μ^+ for at least T_{Gate} in the past
- Single muon detection: only **one** μ^+ and **one** e^+ in observation window ($T_{Gate} \approx 10\mu s$)
- Second μ^+ / e^+ rejection electronically and by rate limitation

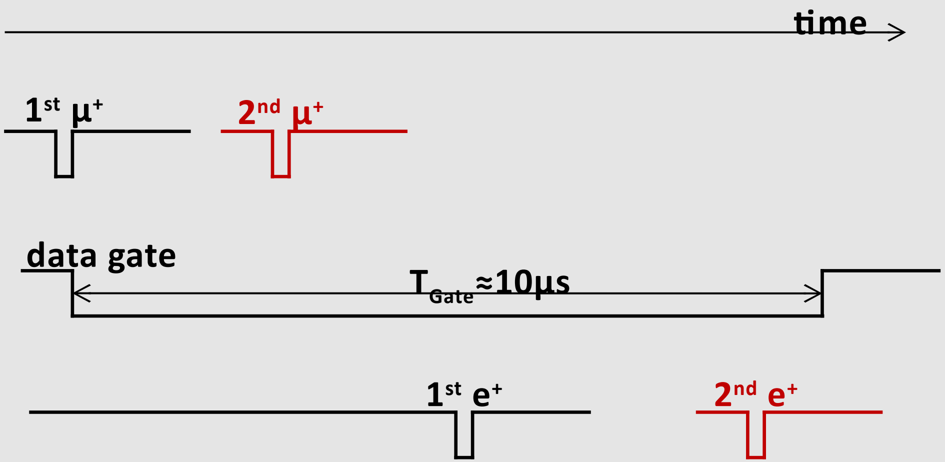
Good Event = (data gate) ^ (1^{st} e^+) ^ (**no** 2^{nd} μ^+) ^ (**no** 2^{nd} e^+)

Rate Limitation on μSR at PSI

Accepted rate (R_{acc})
versus
incoming rate (R_{μ})



Current rate limit for T_{Gate}=10 μs is **~40k μ^+/s**



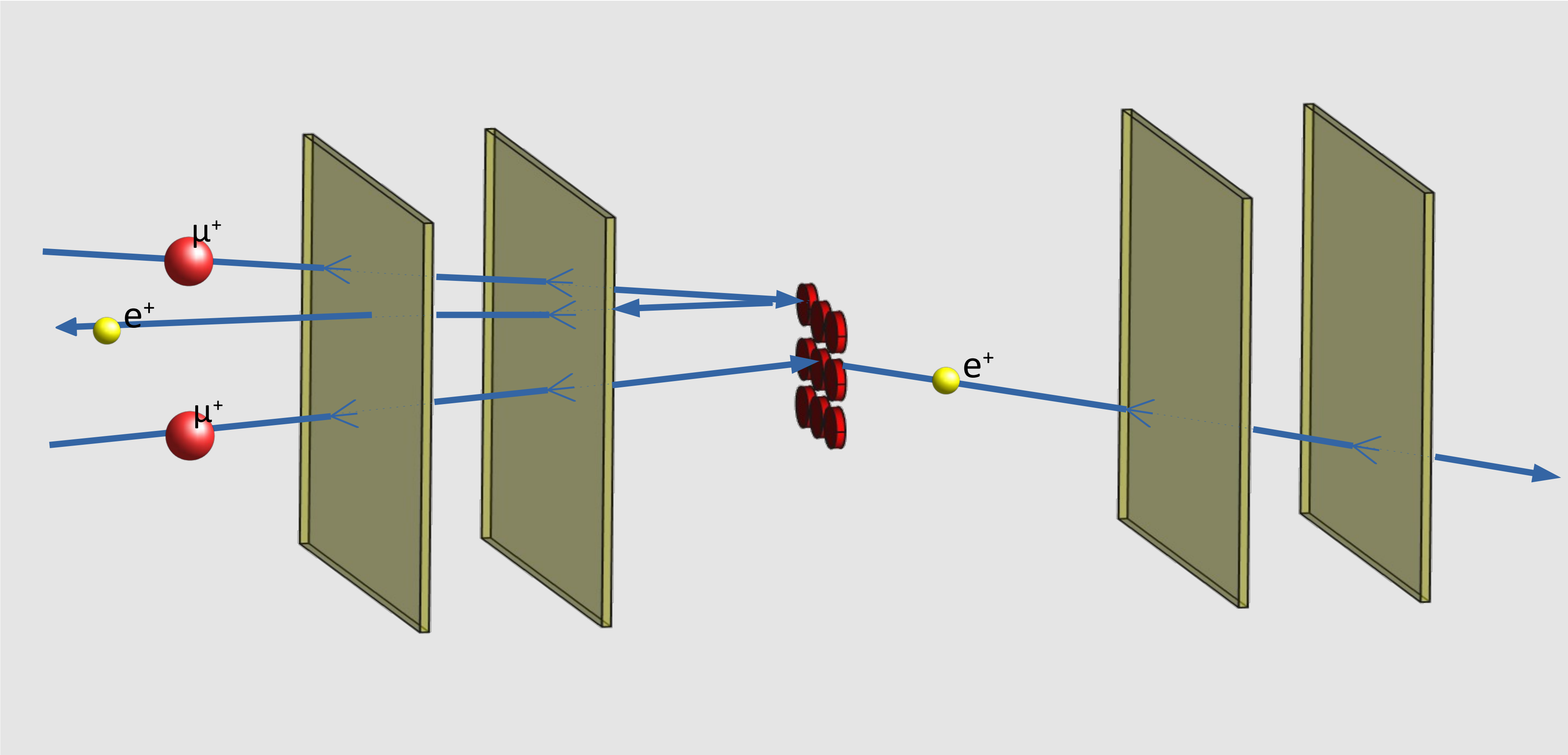
- $1^{st}\ \mu^+$: there was **no** other μ^+ for at least T_{Gate} in the past
- Single muon detection: only **one** μ^+ and **one** e^+ in observation window (T_{Gate}≈10μs)
- Second μ^+ / e^+ rejection electronically and by rate limitation

Good Event = (data gate) ^ ($1^{st}\ e^+$) ^ (**no** $2^{nd}\ \mu^+$) ^ (**no** $2^{nd}\ e^+$)

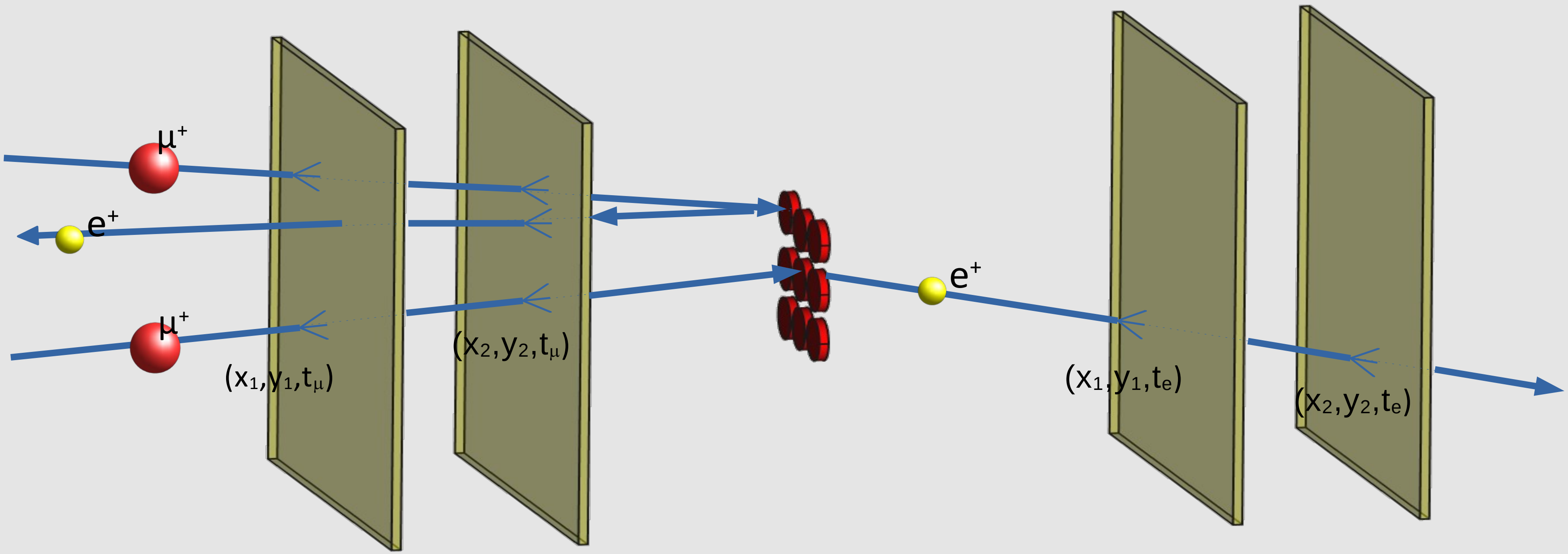
Only 40k Muons/s!

Can we use more?

Vertex Reconstruction Scheme



Vertex Reconstruction Scheme

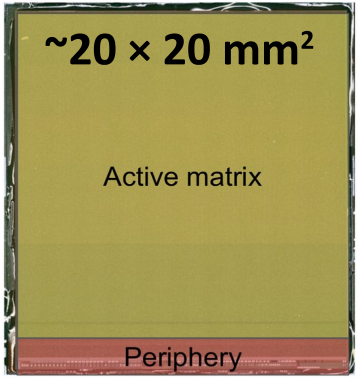


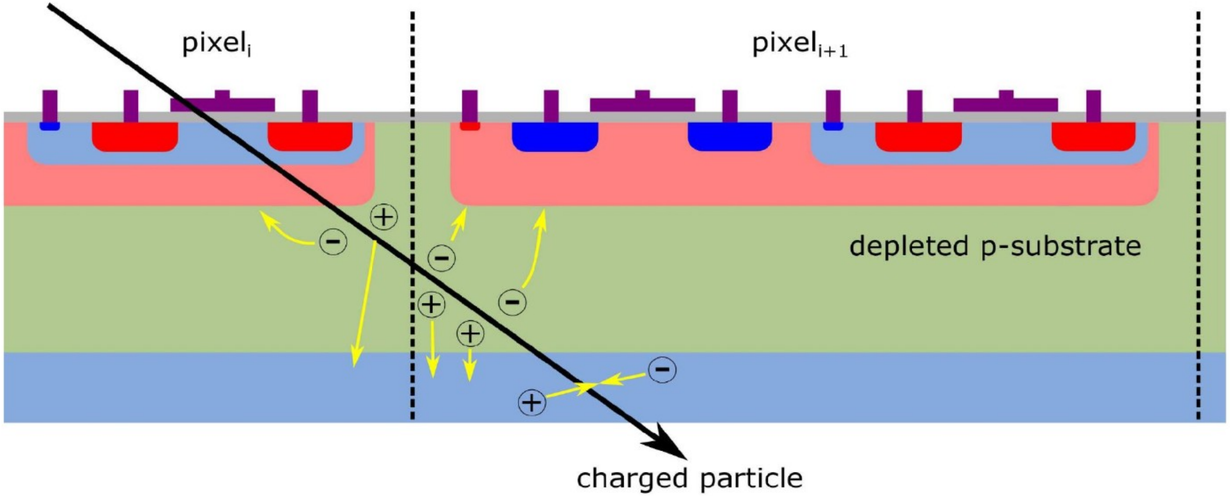
We need detectors that give the position and time of a hit with minimal scattering.

High-voltage monolithic active pixel sensor (HV-MAPS)

Si-Pixel detectors – MuPix11

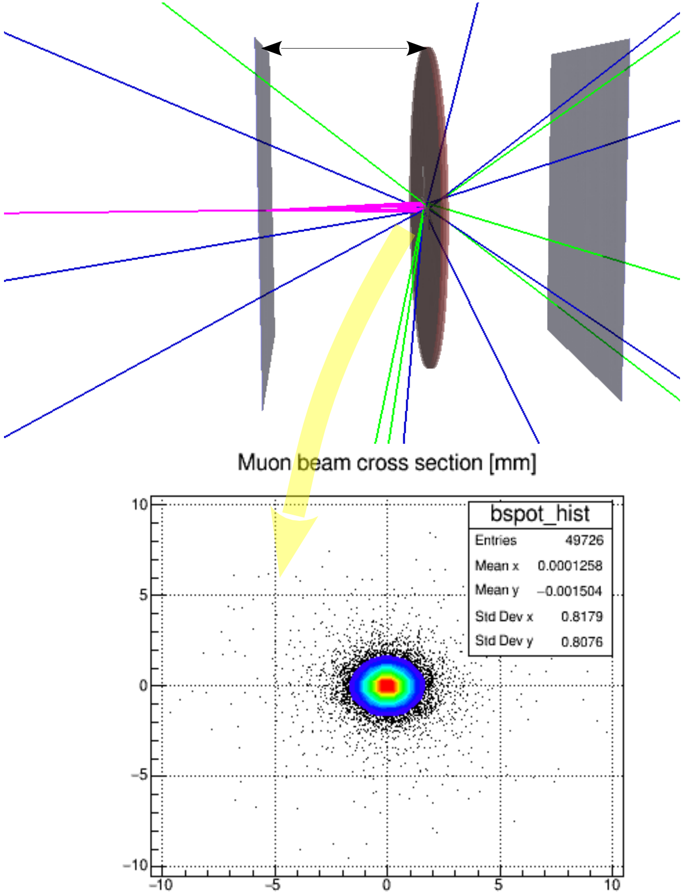
- Developed by the Mu3e collaboration.
- 180 nm HV-CMOS process
- Fully integrated digital readout
- **Can be as thin as 50 micrometers with 80×80 μm² pixel size**
- Continuous readout without trigger
- Less than 20ns time resolution

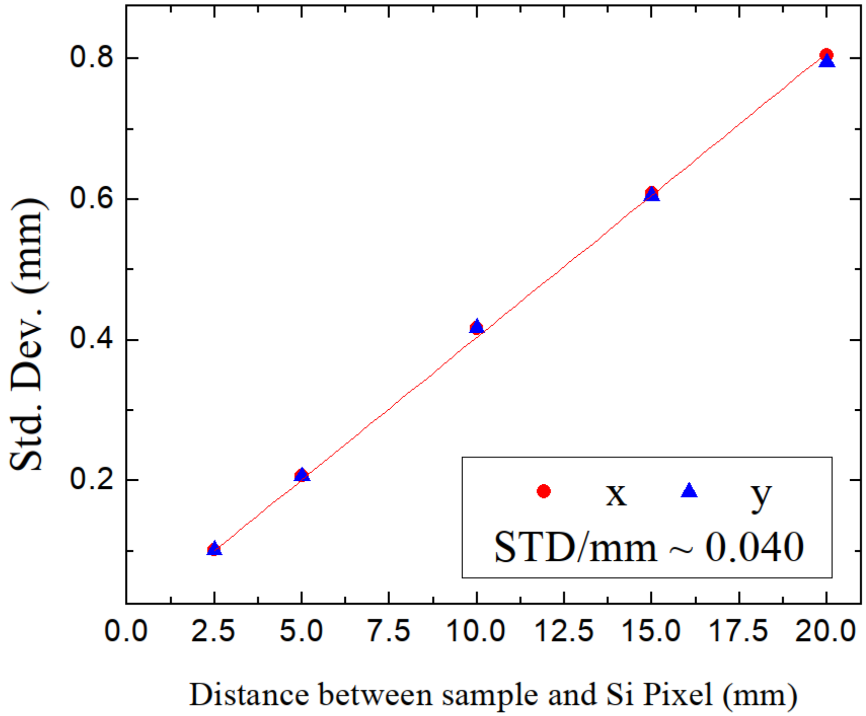




Figures and details obtained from to Thomas Rudzky

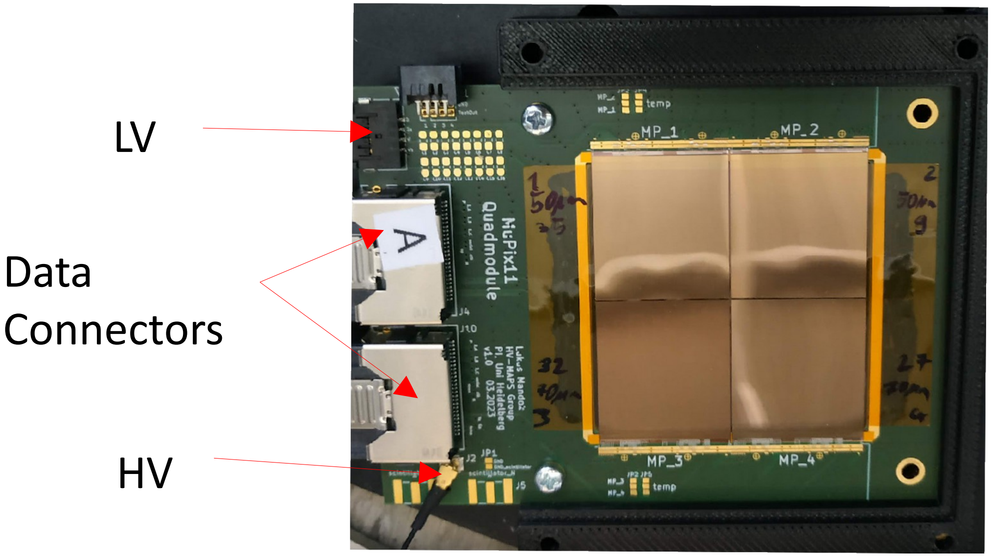
Lateral Resolution Limited by Scattering due to Inner Detectors

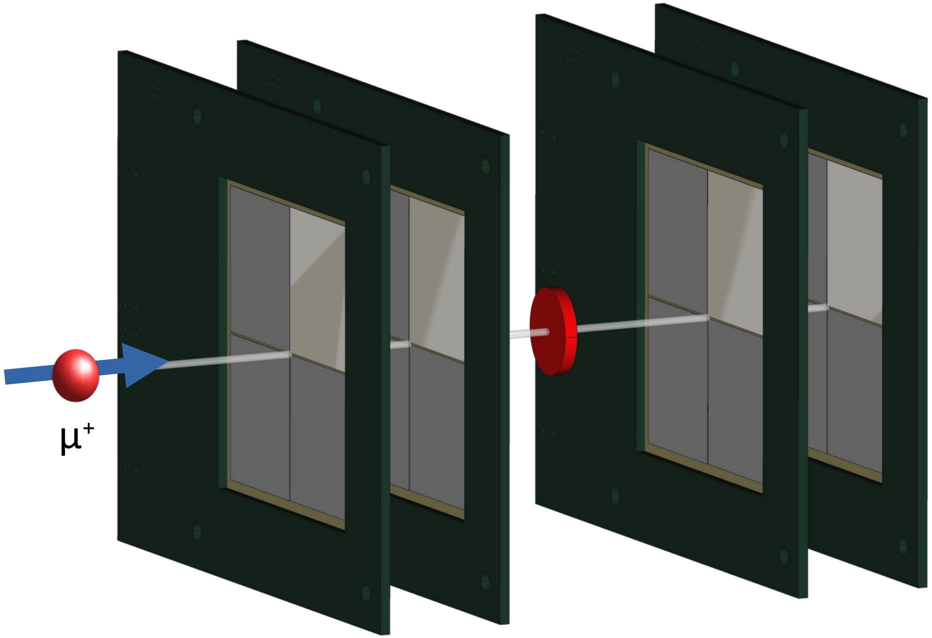




First μSR Experiment with Si-Pixel Detectors

- We constructed a four layer setup.
- Each layer is made of four MuPix11 chips (thickness 50-100 μm) glued onto a 25μm Kapton foil.





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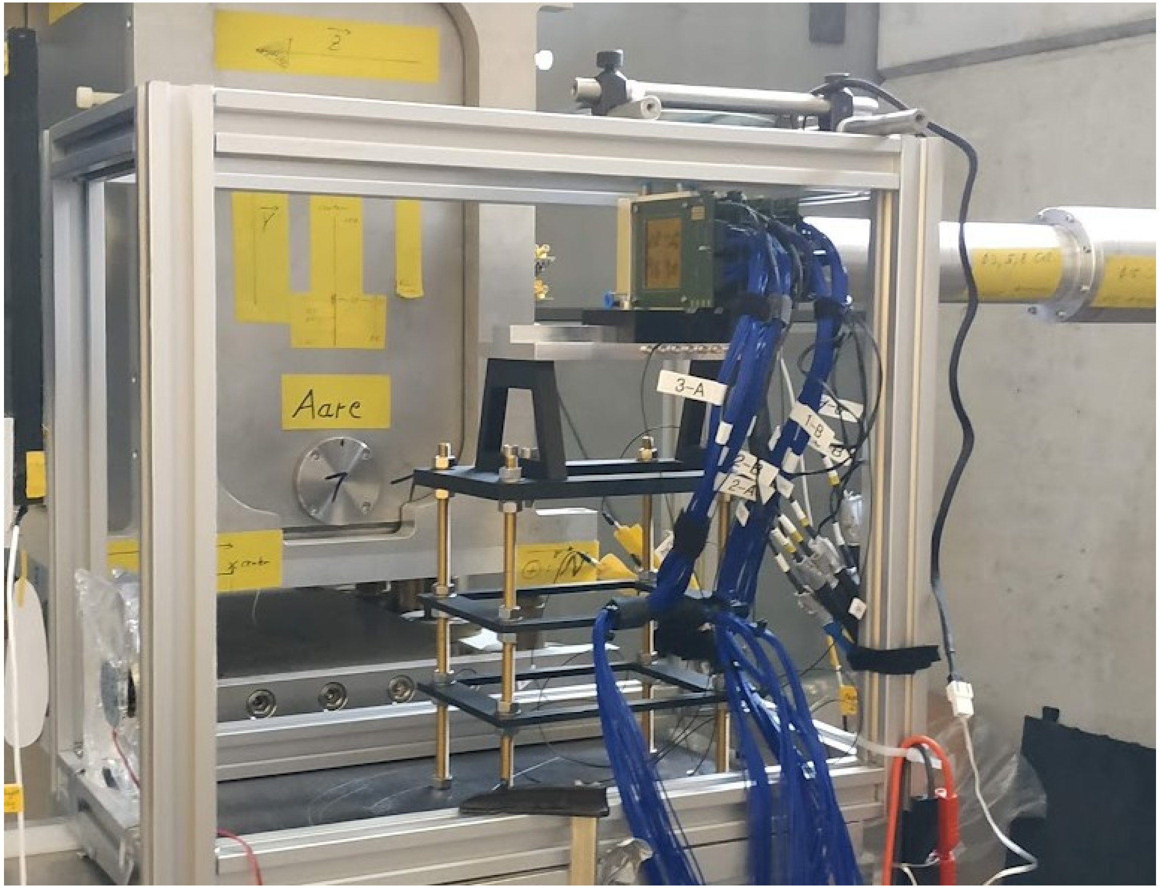
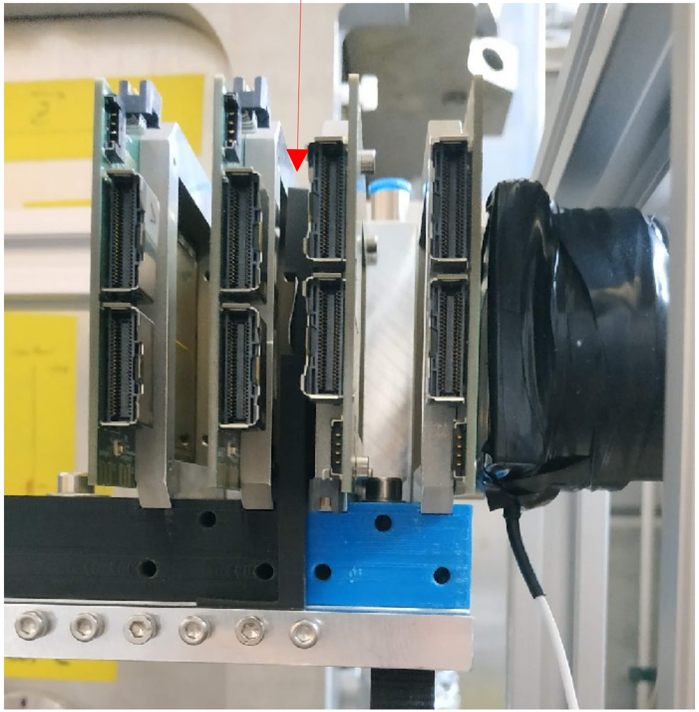
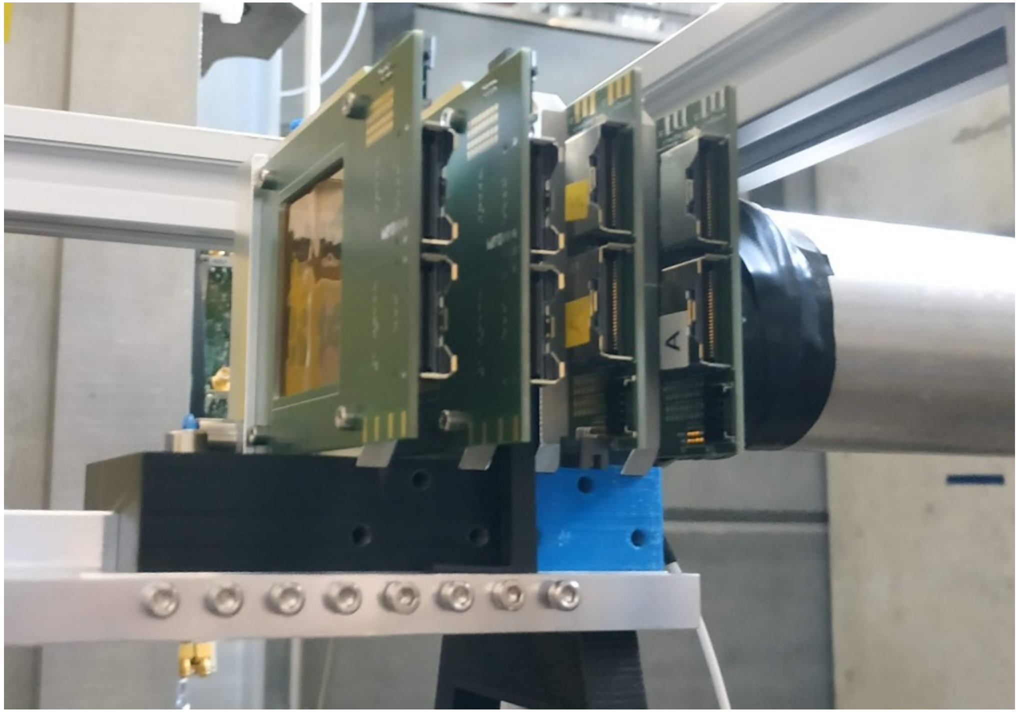


First μSR Experiment with Si-Pixel Detectors

Sample goes here



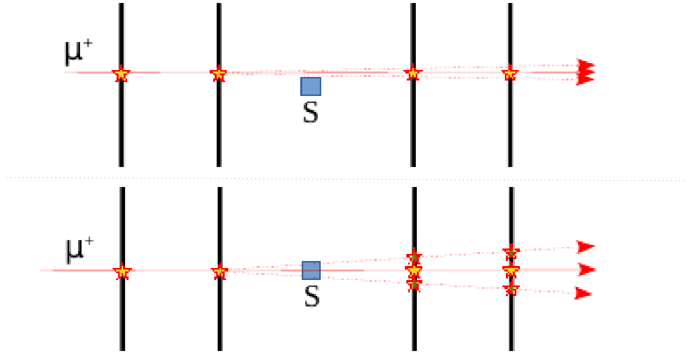


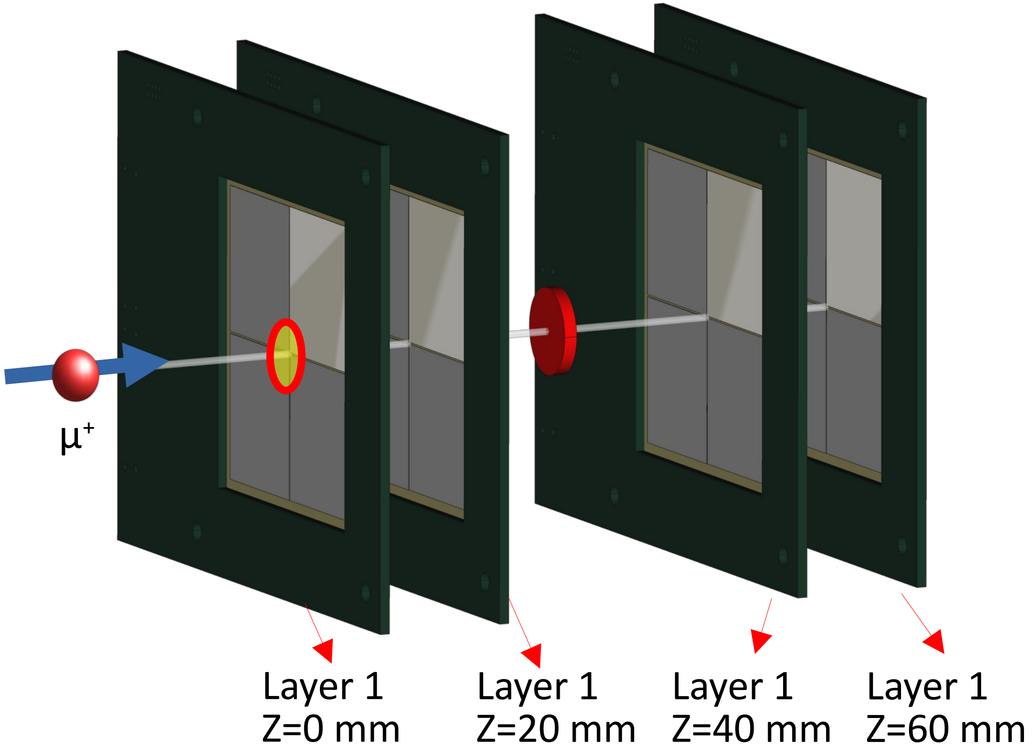
How does the data look like?

- The data collected from the layers comes out as a series of events, position and time stamp:

  (x_i,y_i,t_i) and of course the layer (z_i)

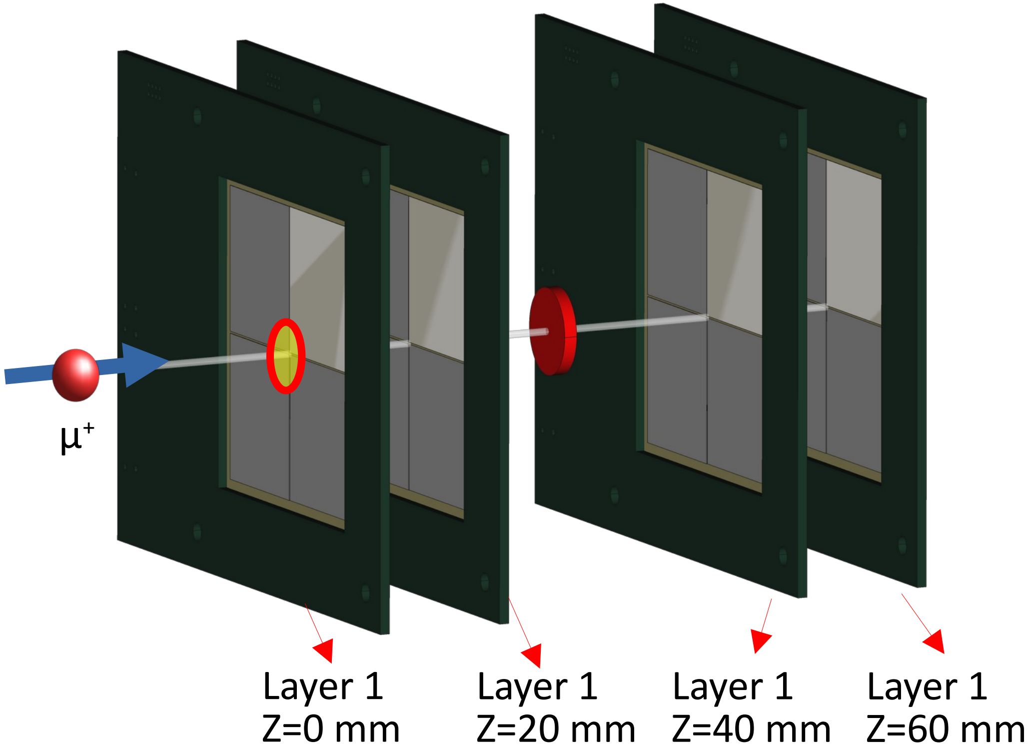
- Allowed tracks **must be** coincidence events in layers (**1&2**) or (**3&4**).





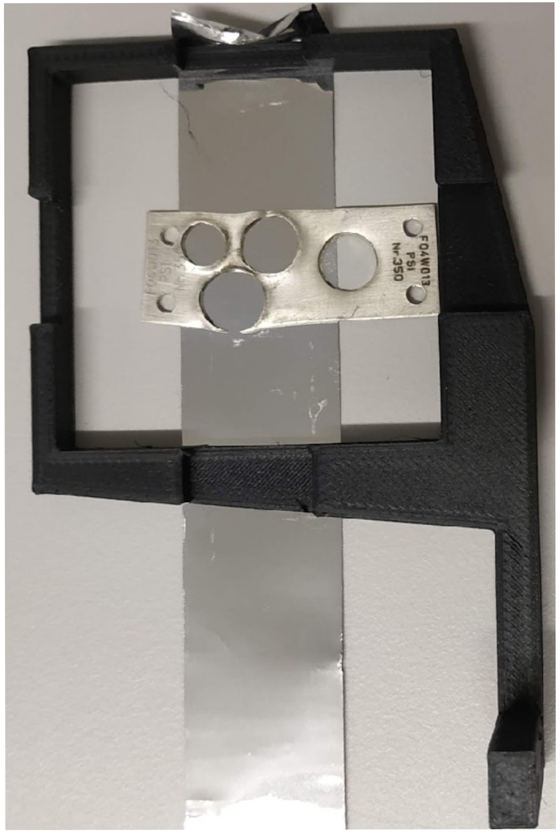
Proposed Algorithm to Extract μSR Spectra

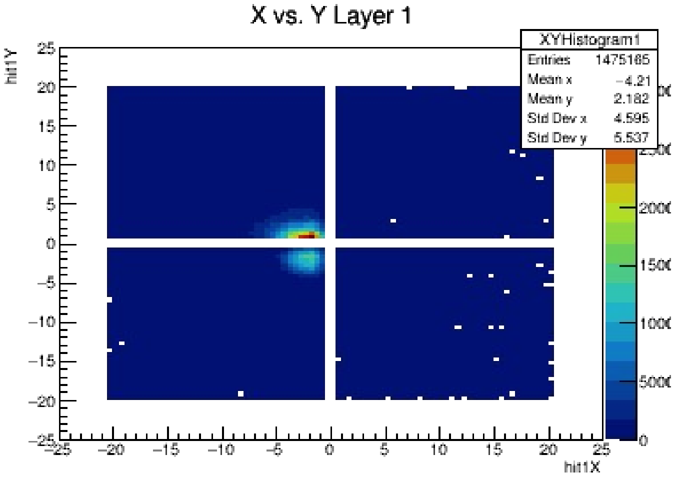
- Any track starting in Layer 1 within a radius of 2 mm from the beam center is a muon.
- Extrapolate this track to the sample position (x_s,y_s).
- Open a (software) data gate of 13 μs
- Within this time, look for tracks (extrapolated to sample - x_s,y_s) starting within 1mm from (x_s,y_s).
- There should be only one such track, if so, it is the emitted positron. If not ignore and move on...



Does this actually work?

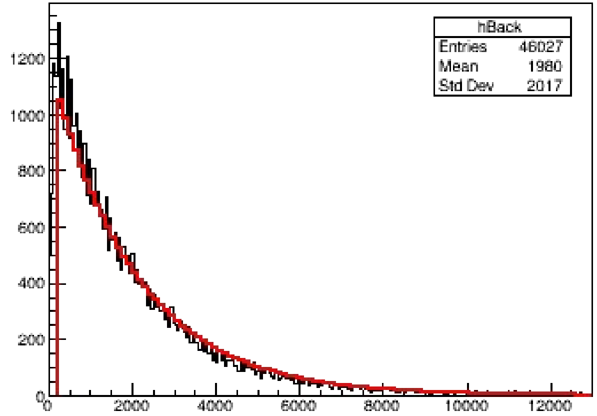
First Example – Can we resolve geometric details?



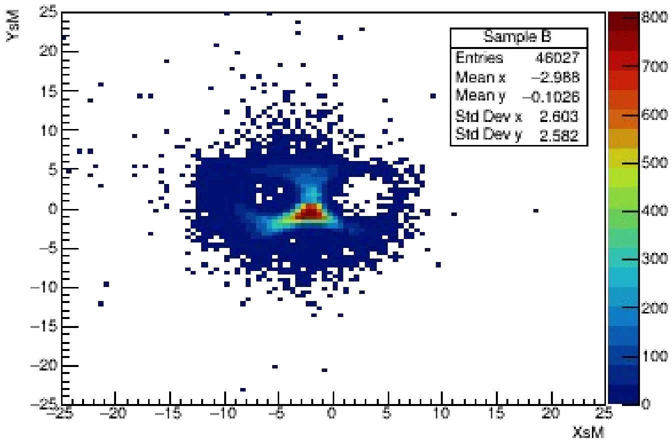


First Example – Can we resolve sample details?

Time ($t_{positron} - t_{muon}$) histogram



Vertex of valid events recorded In the upstream set of detectors



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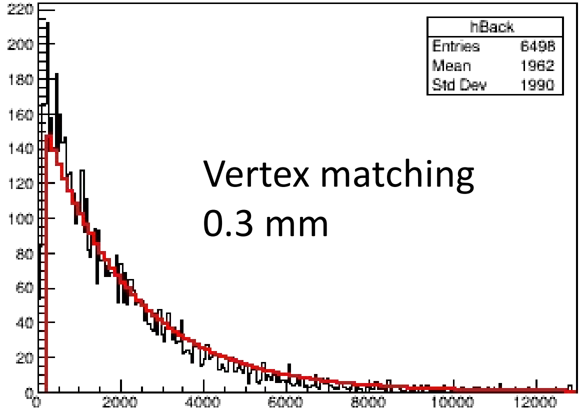

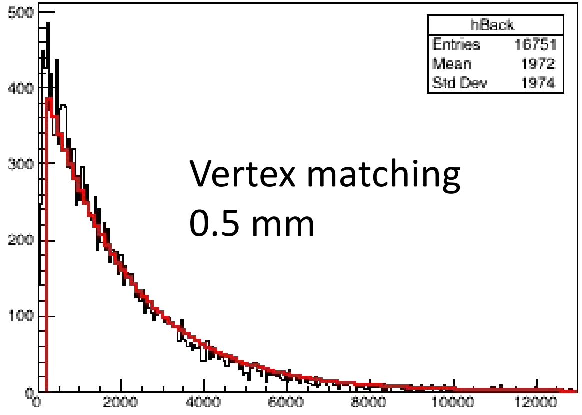

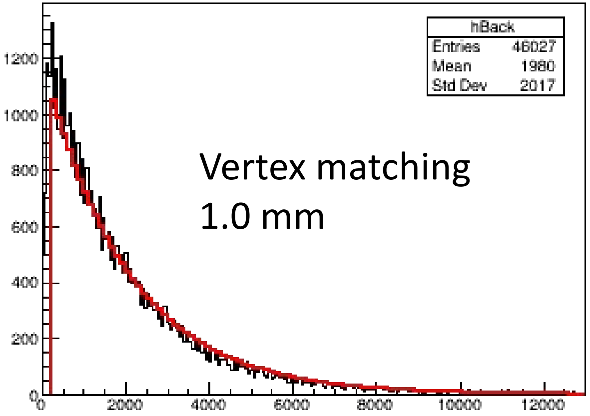

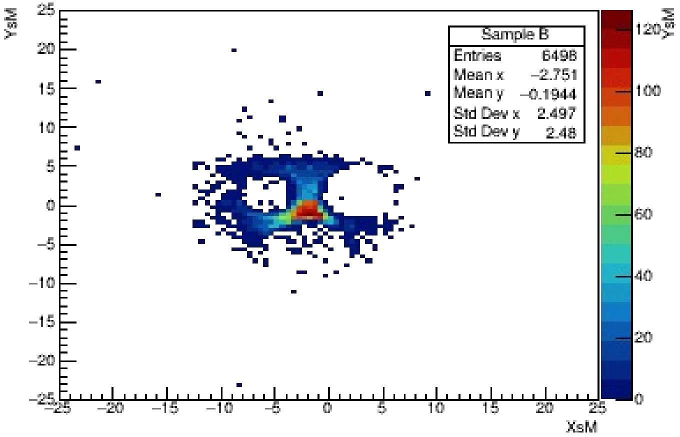

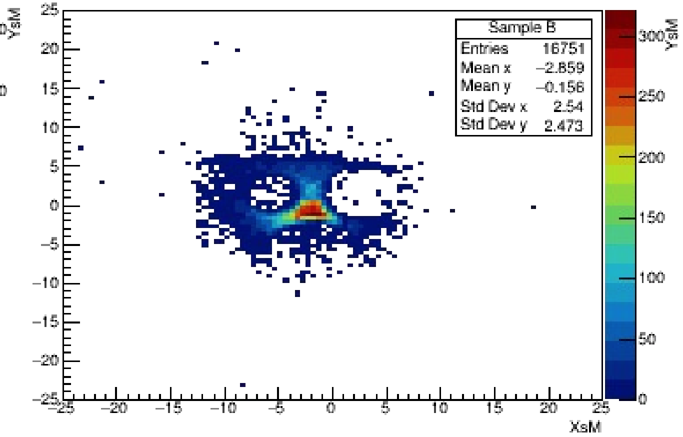

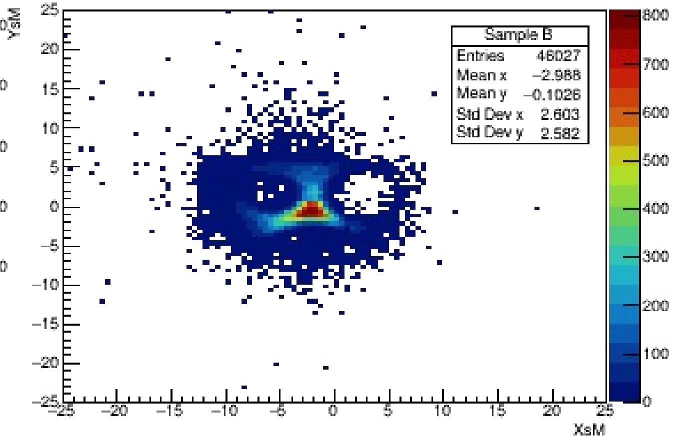

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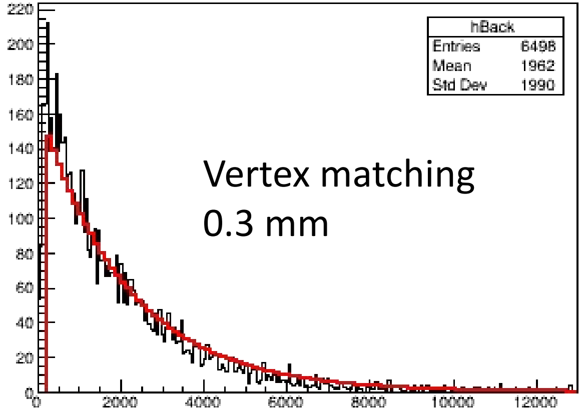
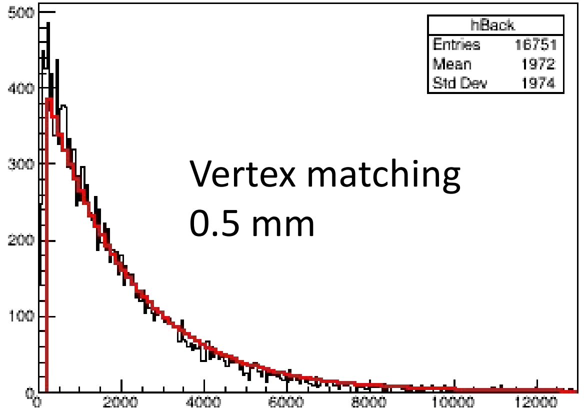
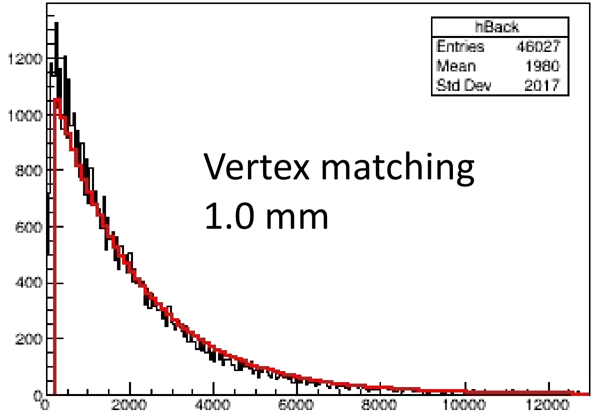
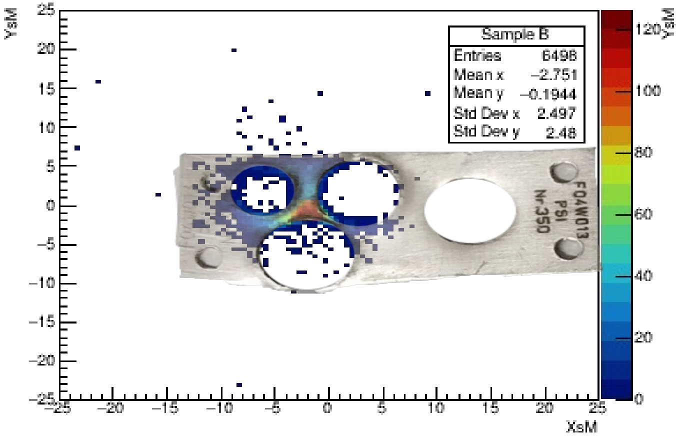
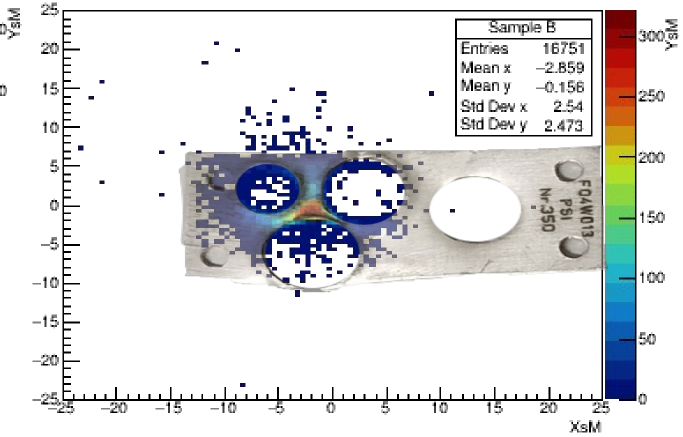
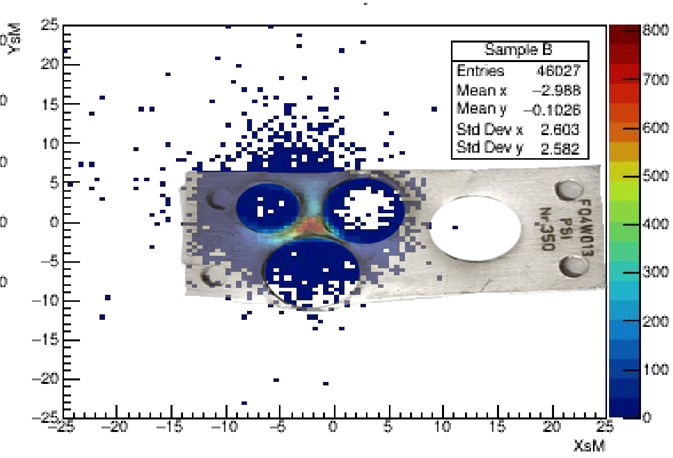






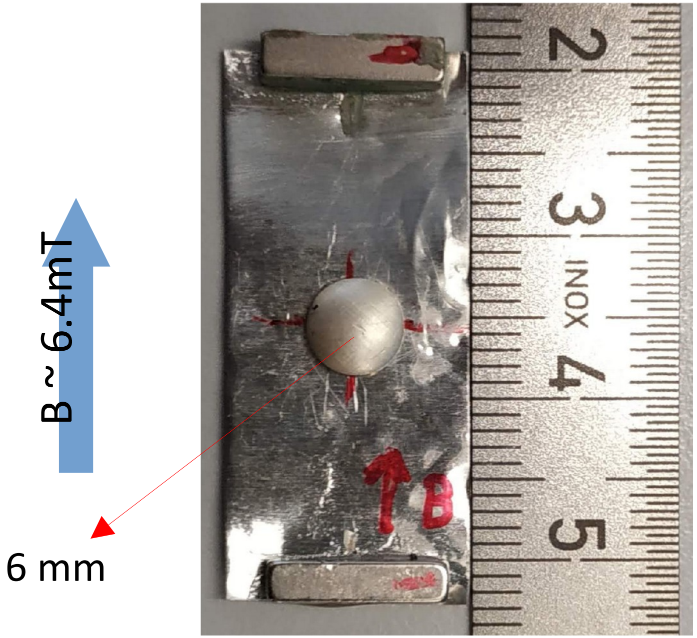






Second Example - µSR Precession Signal

- For a precession we need a magnetic field… using magnets.



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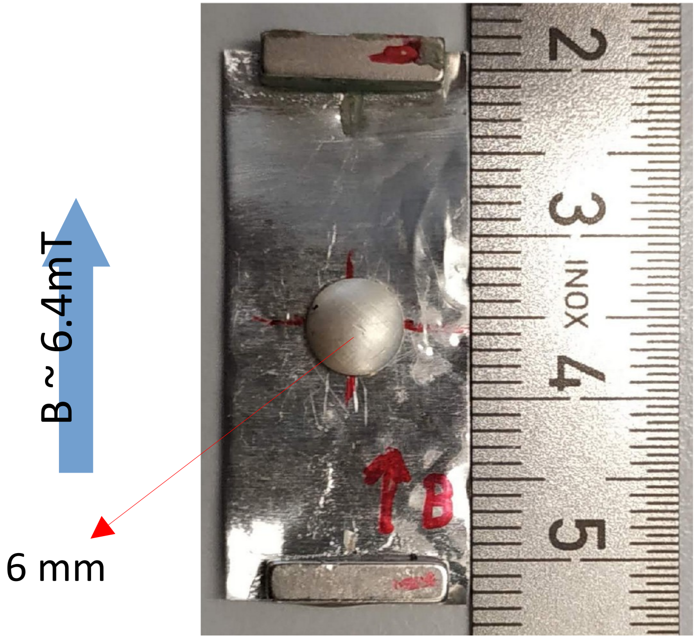

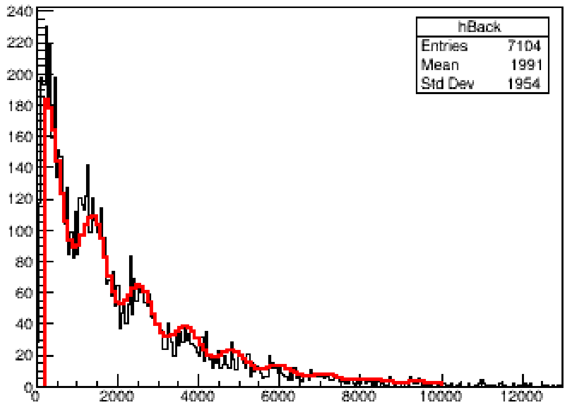

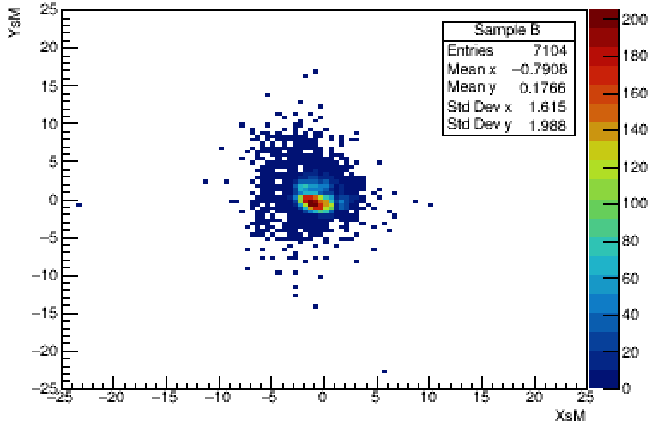

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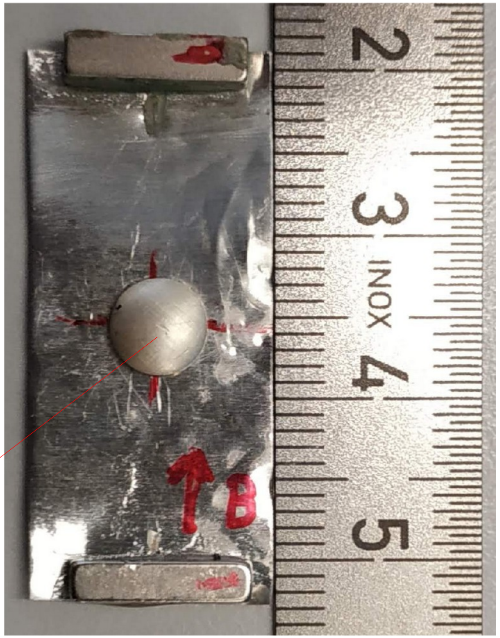
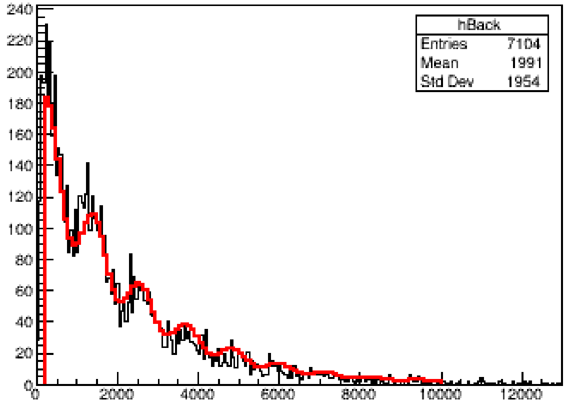
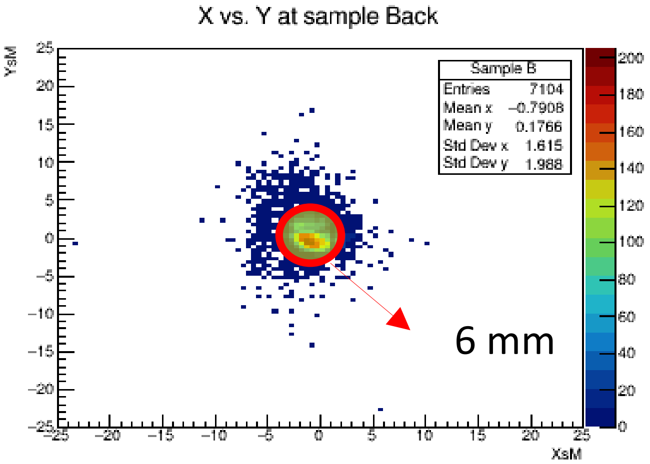
B ~ 6.4mT



6 mm

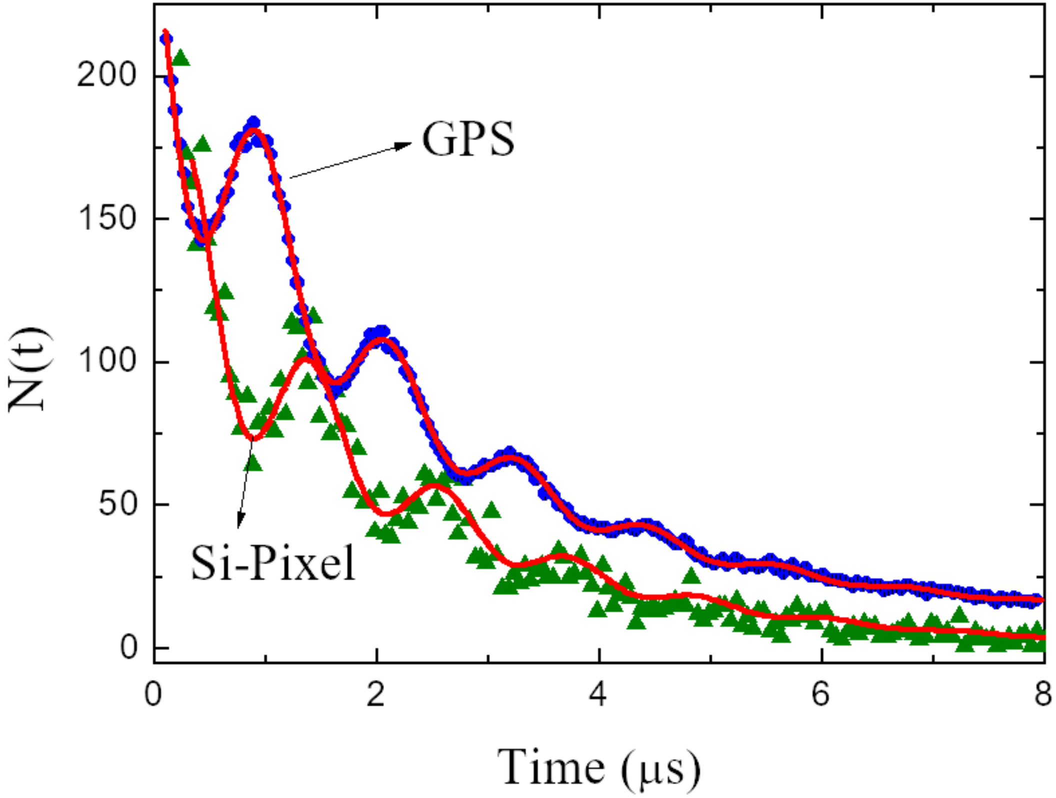




6 mm

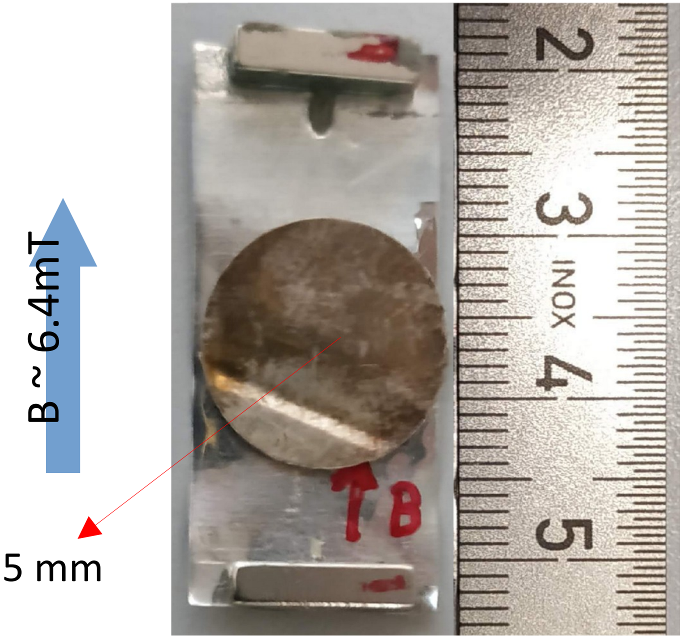
Second Example - μSR Precession Signal

- Comparison between a standard spectrometer (GPS) and our Si-Pixel spectrometer shows:
  - Same precession frequency and damping, i.e. the same magnetic field and width of field distribution on the sample.
  - Lifetime of muon
  - Si-Pixel has **no accidental background**



Third Example - μSR Precession Signal, Magnetic Imaging

- The larger samples show less «wiggles» due to the large field distribution.



15 mm

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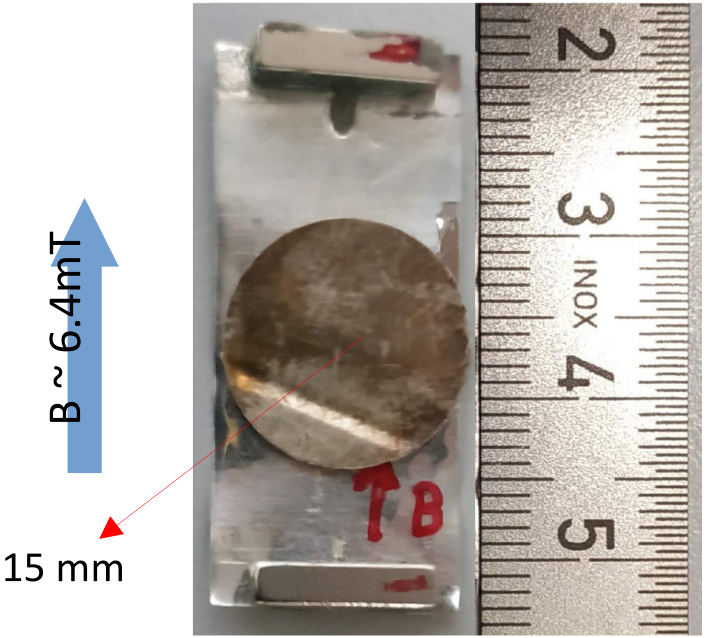

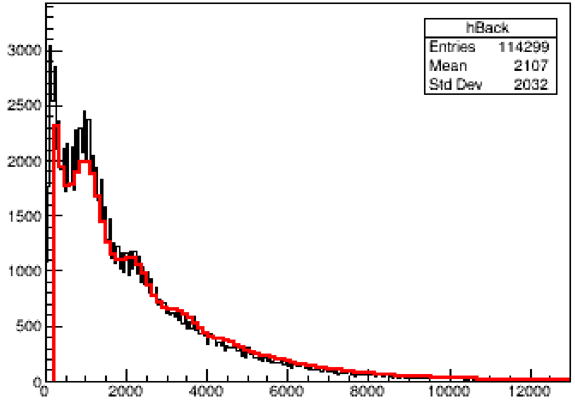

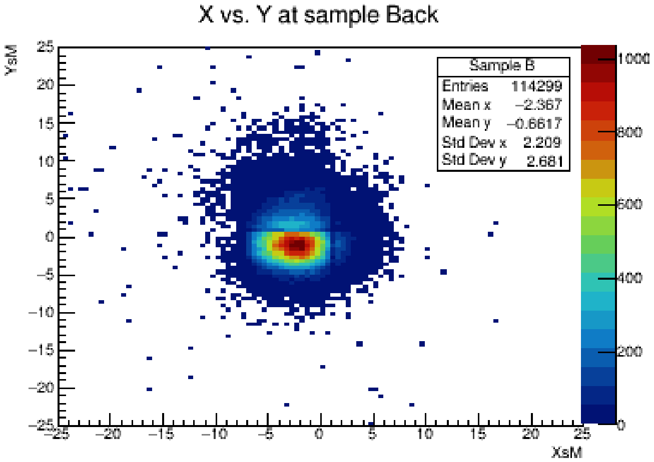

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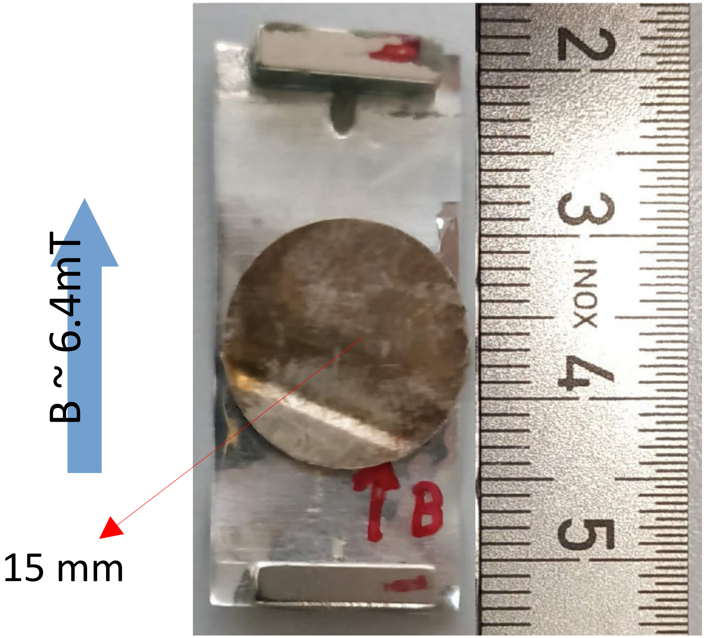

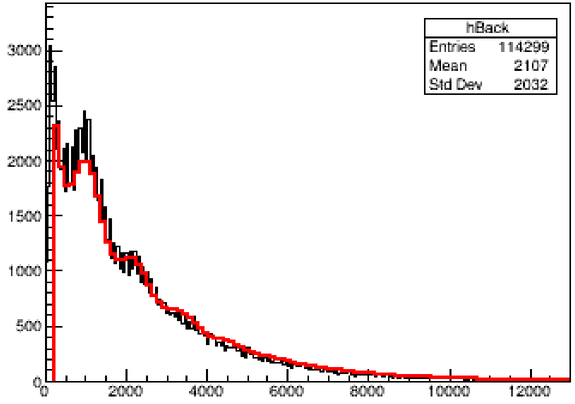

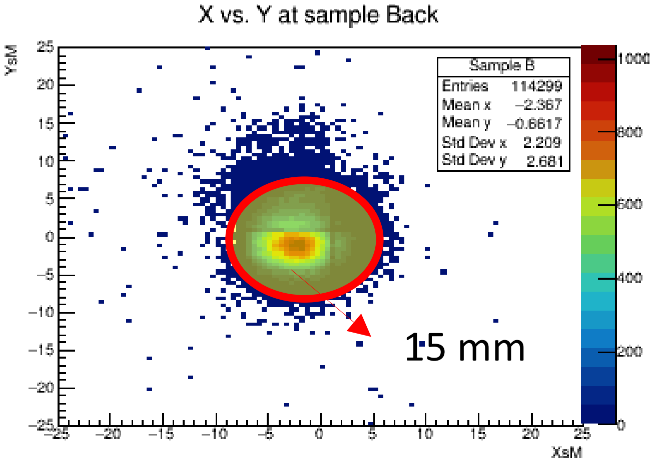

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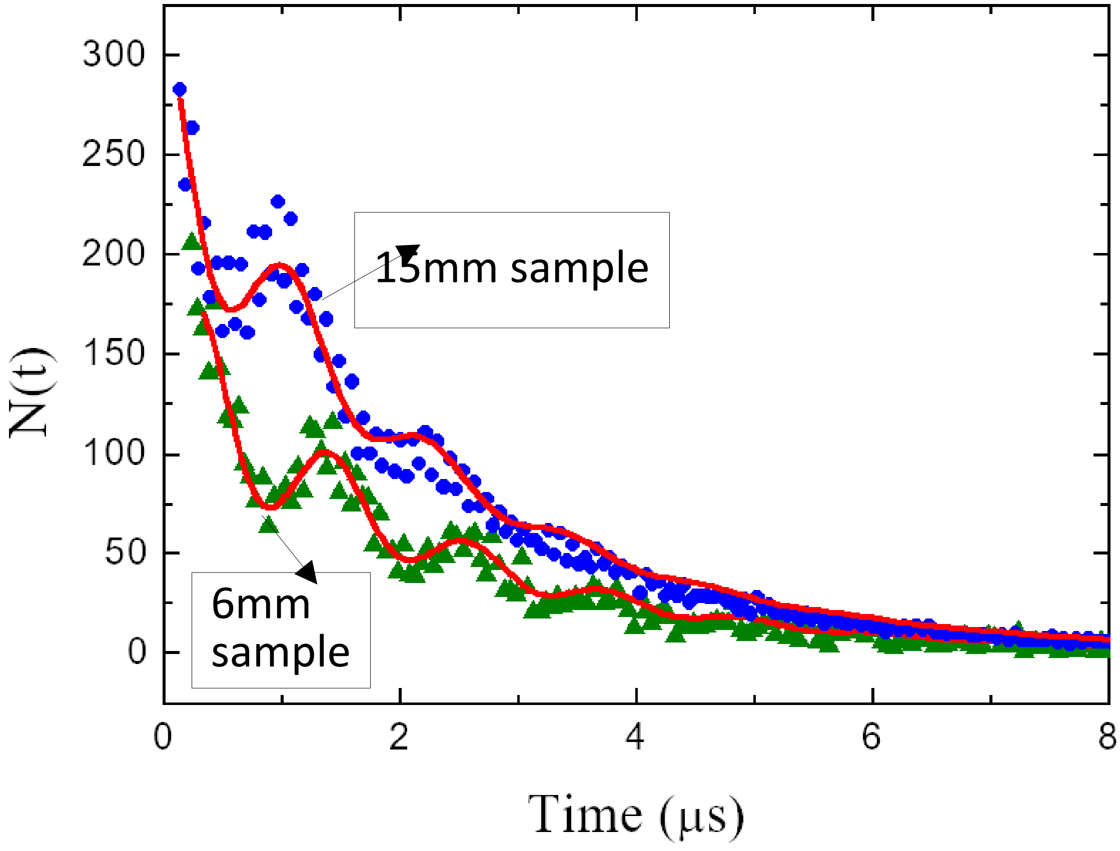

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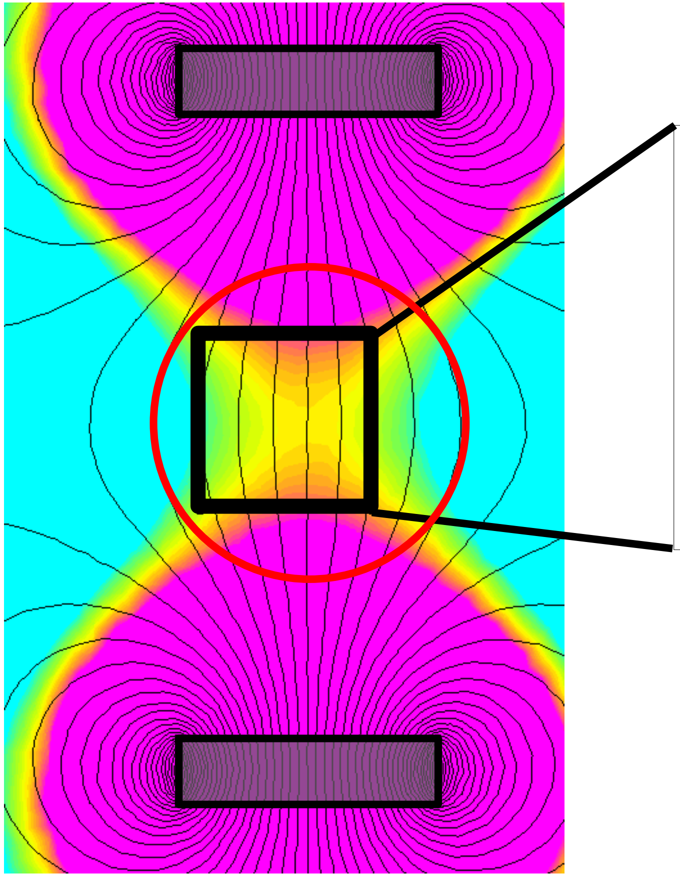
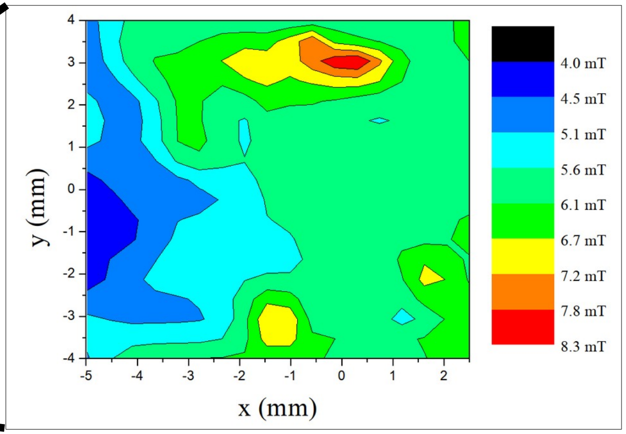




The magnetic field sensed by muons within 1mm diameter

Summary and Conclusions

- We can do μSR using vertex reconstruction schemes
- We can reach at least ~1mm lateral resolution
- Si-Pixel detectors should give a quantum leap in our ability to perform μSR measurements.
- We will be able to measure millimeter sized sample, perform measurements on multiple sample simultaneously and much more...

Thanks to ...

PSI

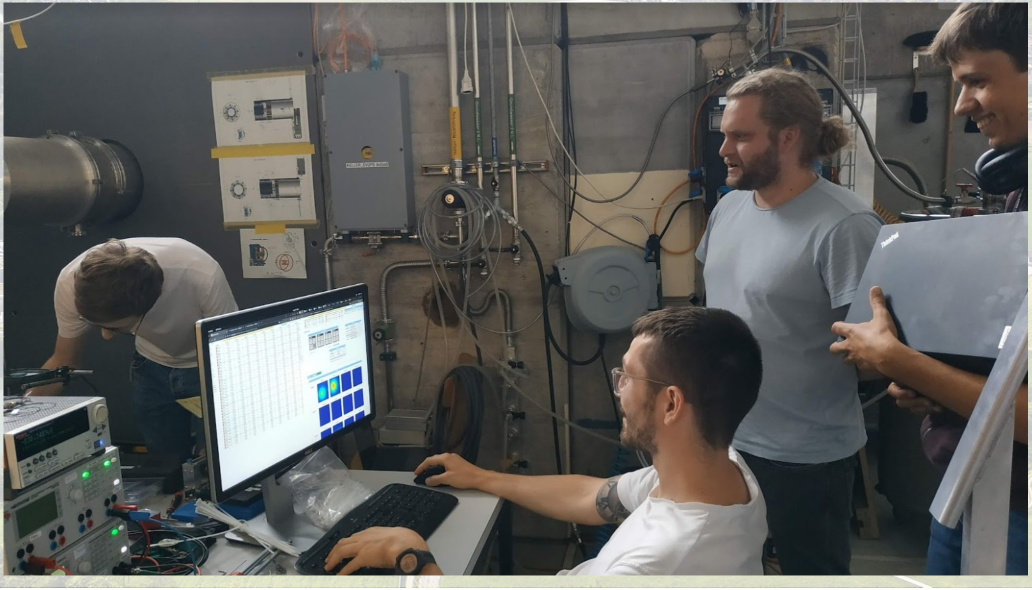
Thomas Prokscha
Hubertus Luetkens
Jonas Krieger
Lea Caminada (UZH)
Hans-Christian Kaestli
Tilman Rohe
Frank Meier

Heidelberg

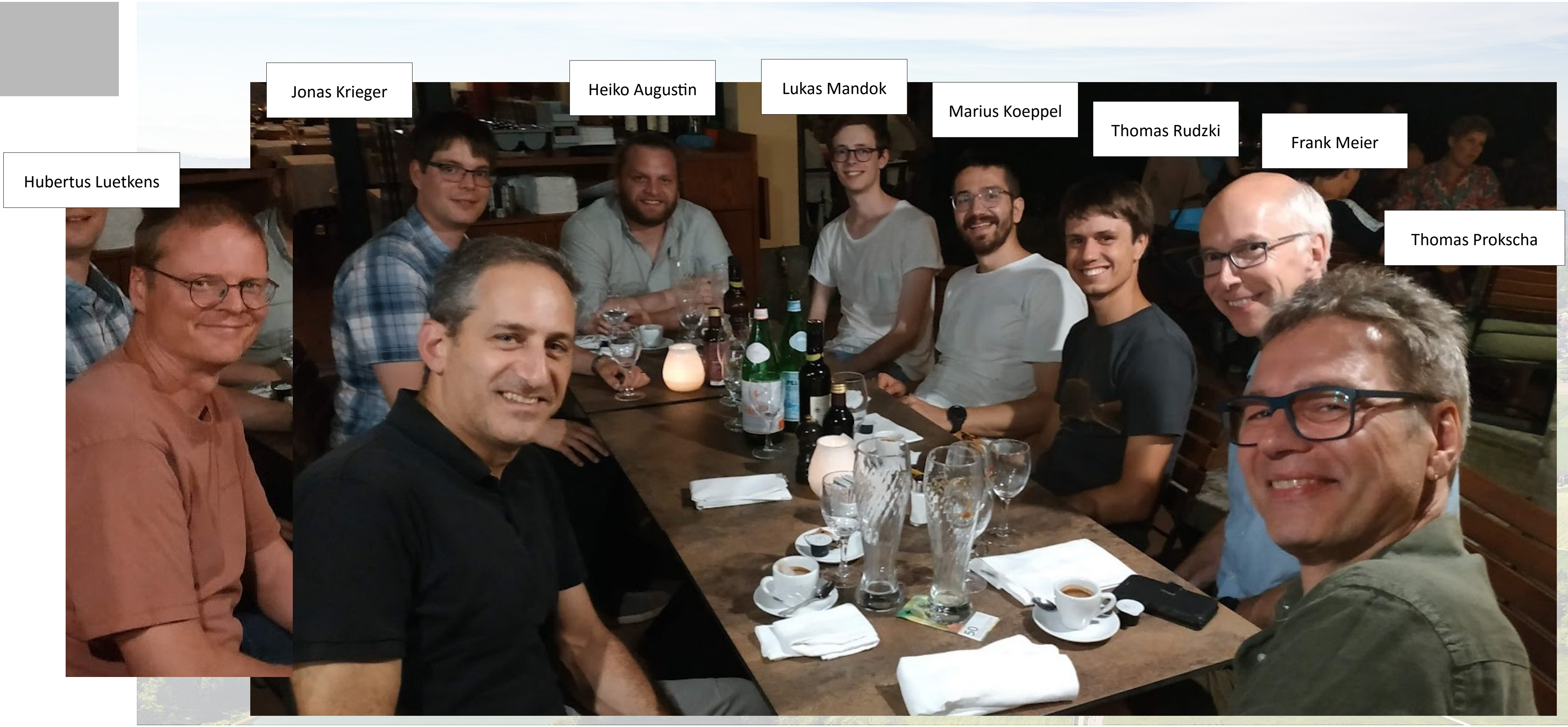
Thomas Rudzki (Postdoc)
Lukas Mandok (MSc)
Heiko Augustin (Postdoc)
Andre Schoening

Mainz

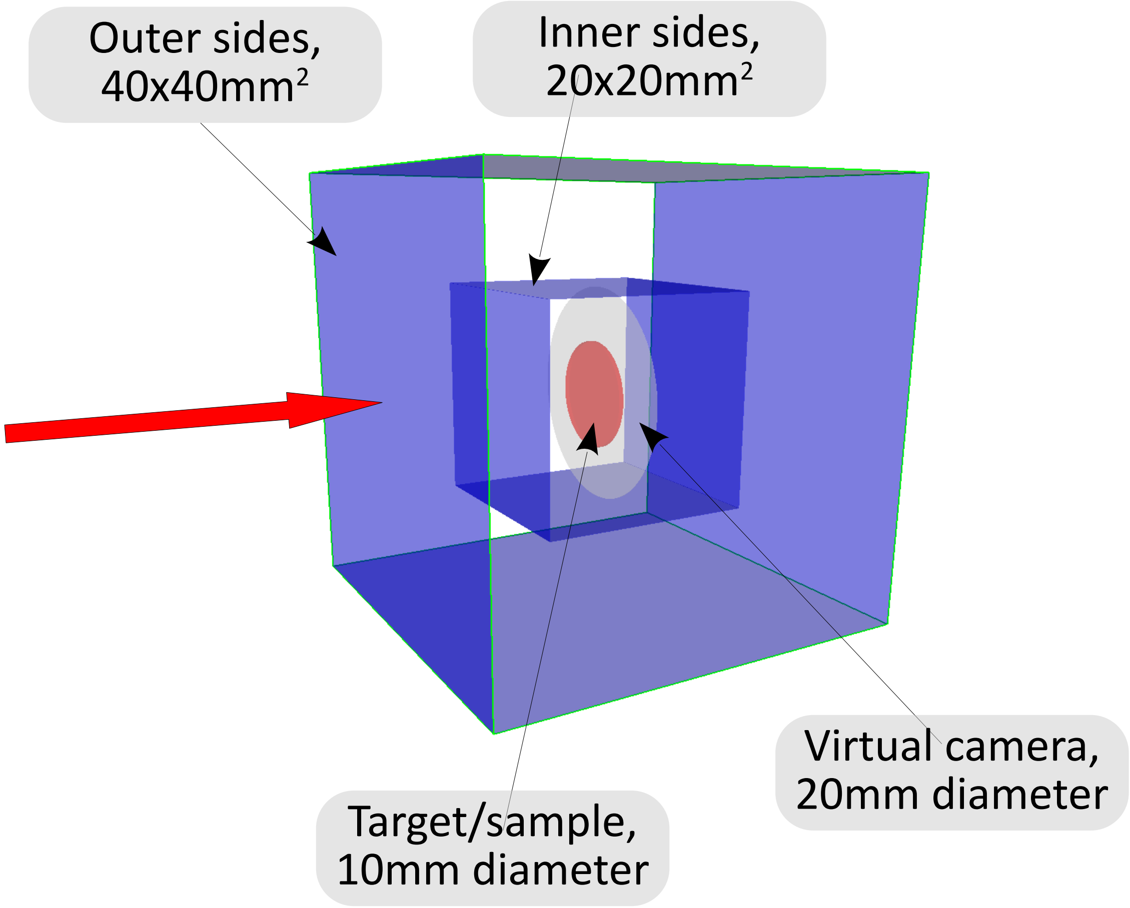
Marius Koeppel (PhD)

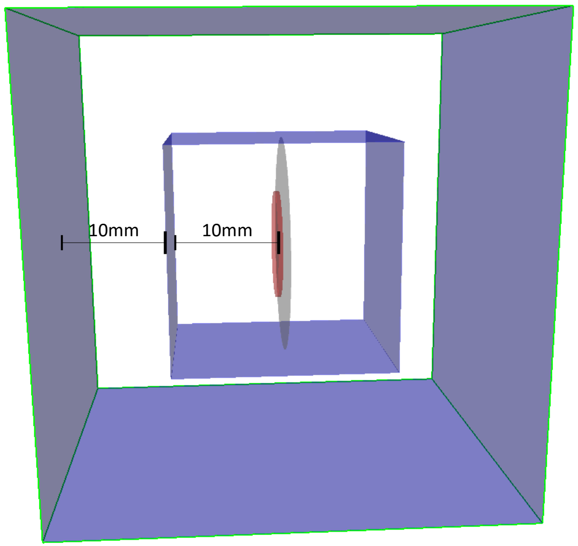


Thanks

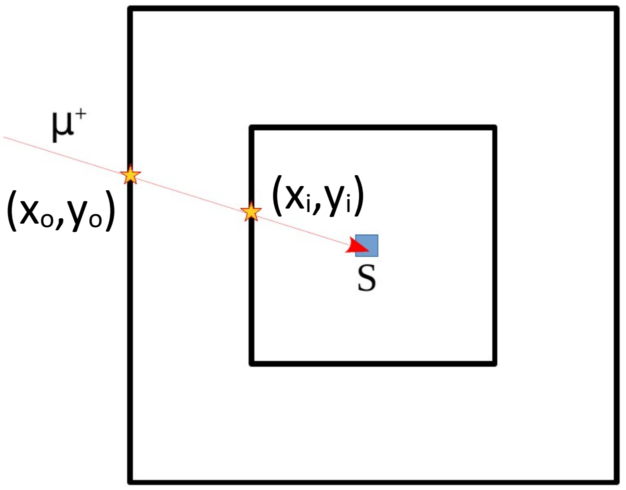

Jonas Krieger
Heiko Augustin
Lukas Mandok
Marius Koeppel
Thomas Rudzki
Frank Meier
Hubertus Luetkens
Thomas Prokscha

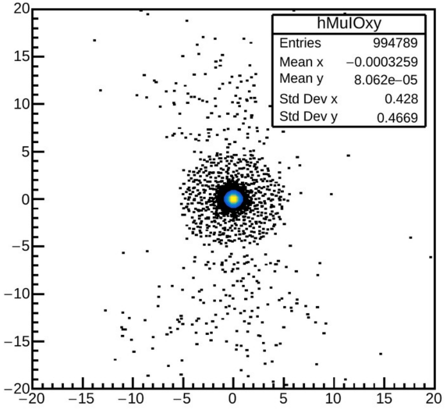
Simulated detector geometry



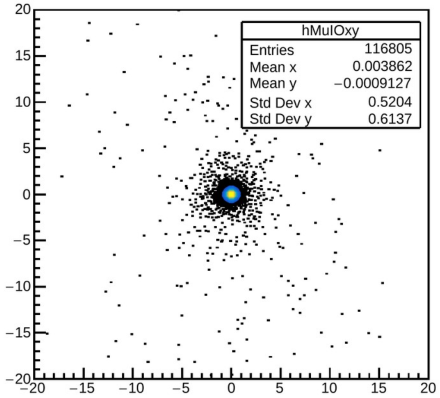


How well does vertex reconstruction work?





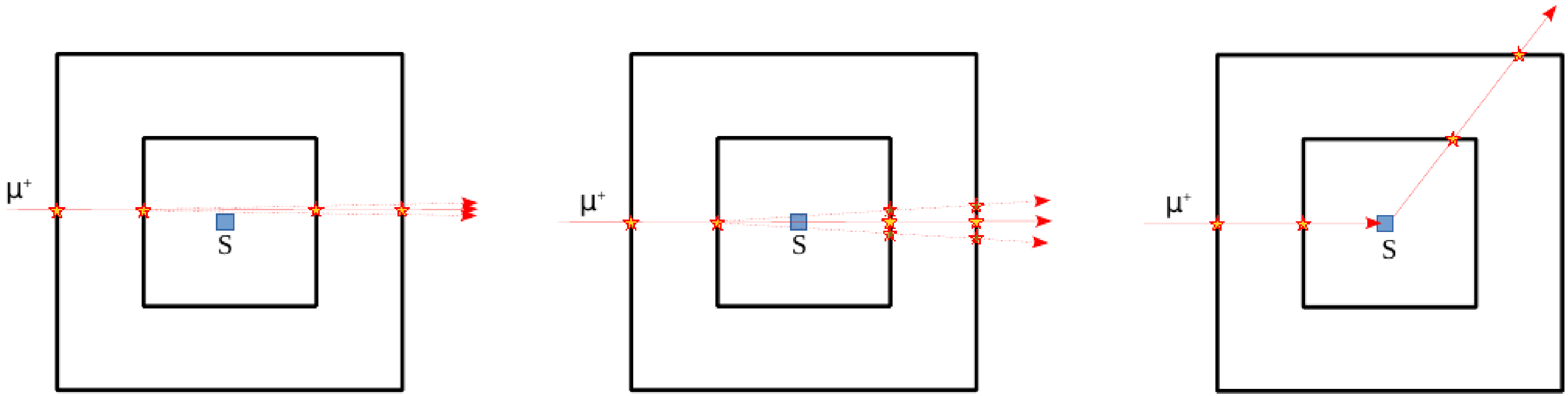
Infinitely sharp beam



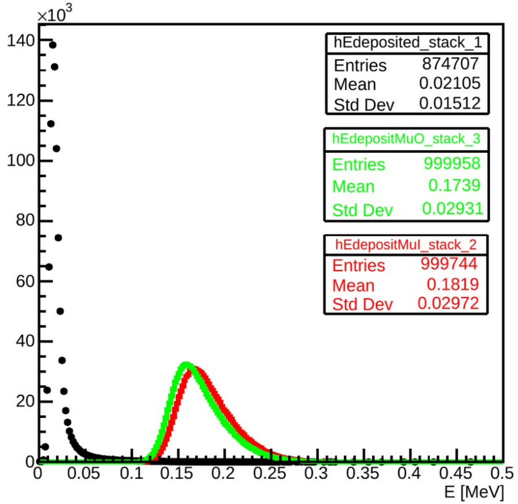
Gaussian beam profile with $\sigma_{x,y}$=10mm

- From (x_o,y_o) and (x_i,y_i) extrapolate to sample position → (x_s,y_s)
- How far is (x_s,y_s) from the actual landing position of the muon (taken from the “camera”).
- Even with a large beam profile we get RMS~0.6 mm with average zero.
- Adding 20μ Kapton adds ~10% to the RMS.

Veto events

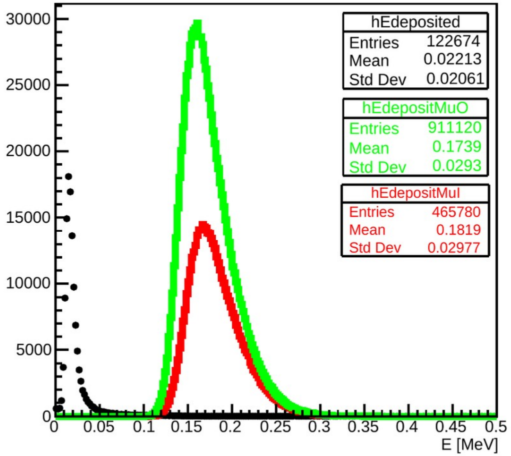


(a) (b) (c)



Infinitely sharp be

n beam profile with c

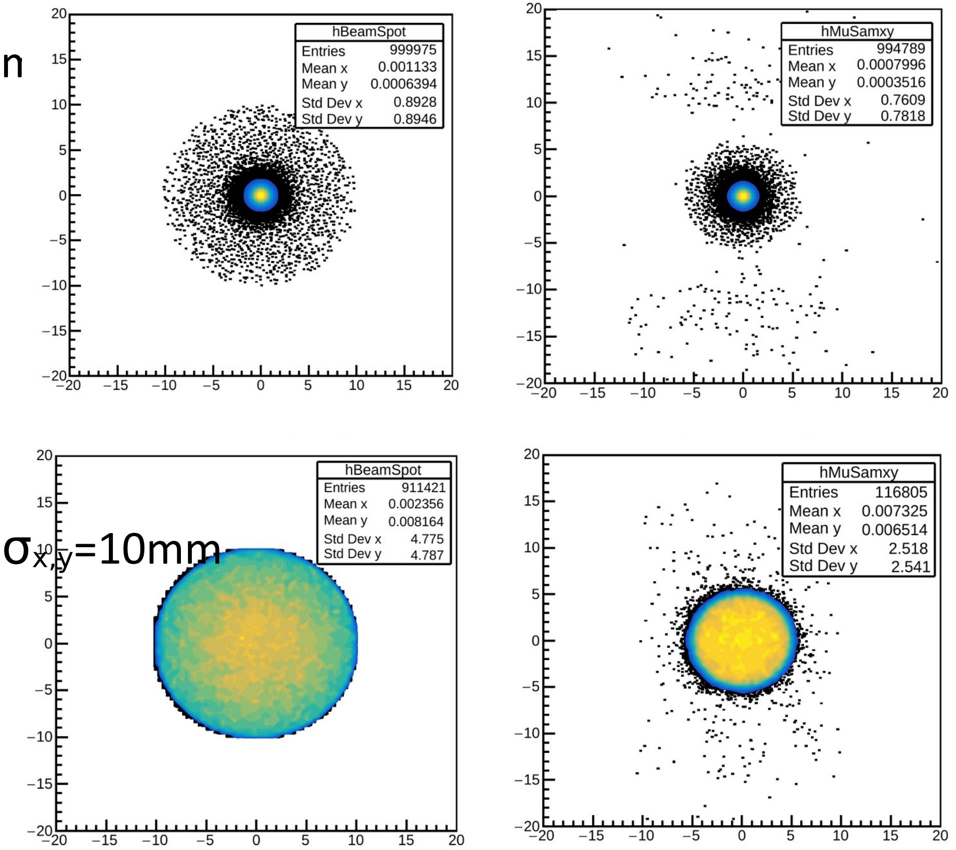


Beam size

On "camera" | On sample with veto

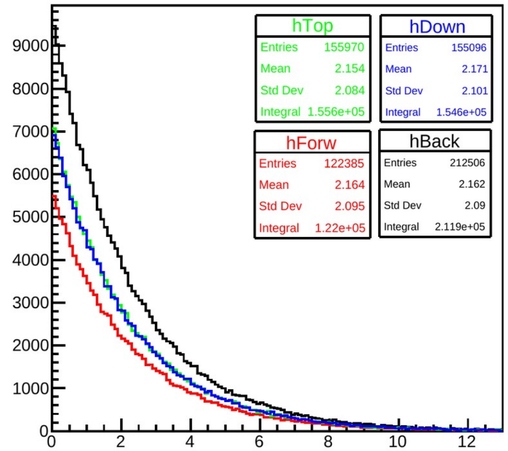
Infinitely sharp bean

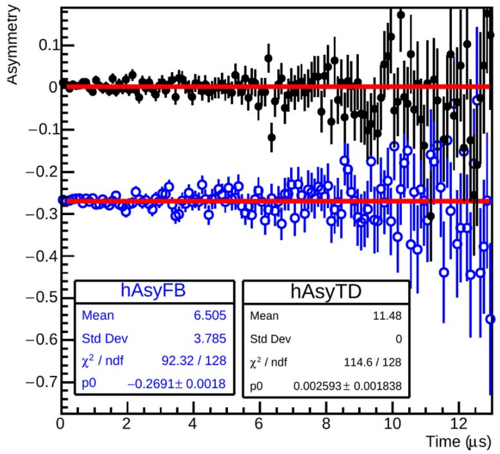
Gaussian beam profile with $\sigma_{x,y}$=10mm



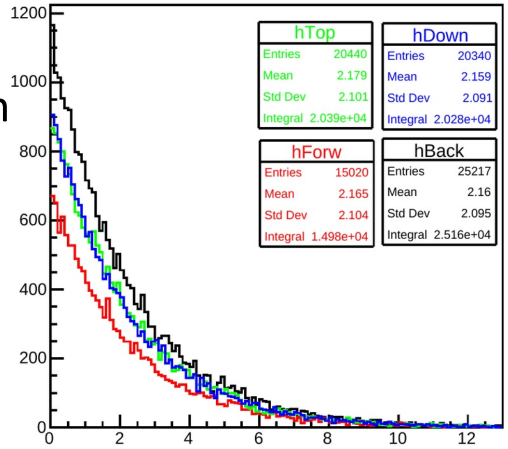
What about μSR measurements

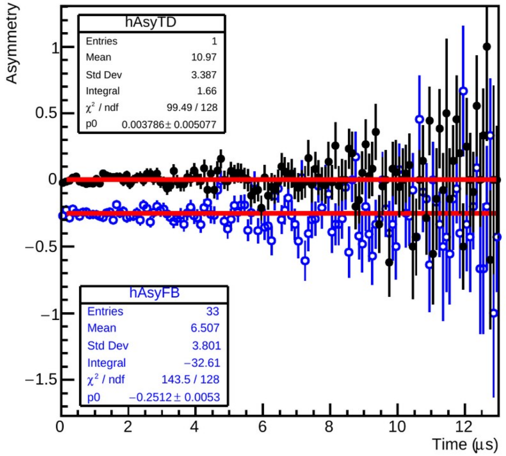
Infinitely sharp beam



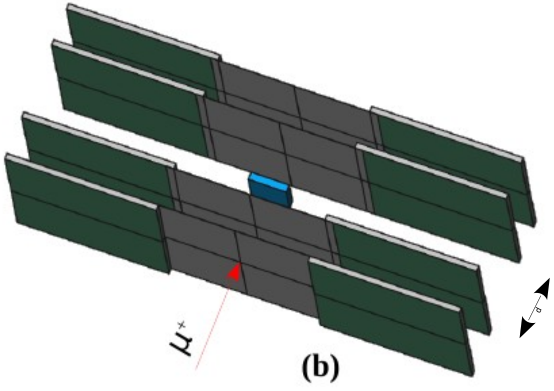


Gaussian beam profile with $\sigma_{x,y}$=10mm



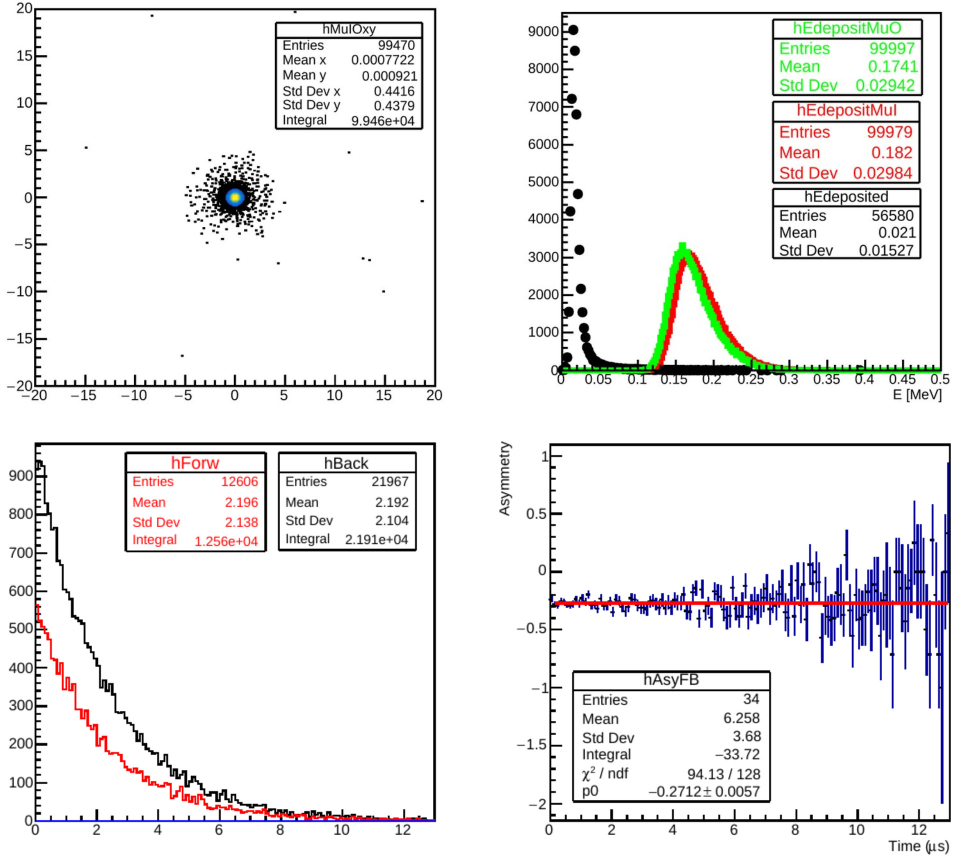


What about the quads?

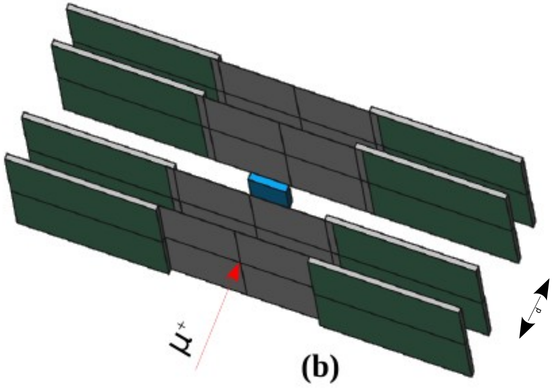


Infinitely sharp beam

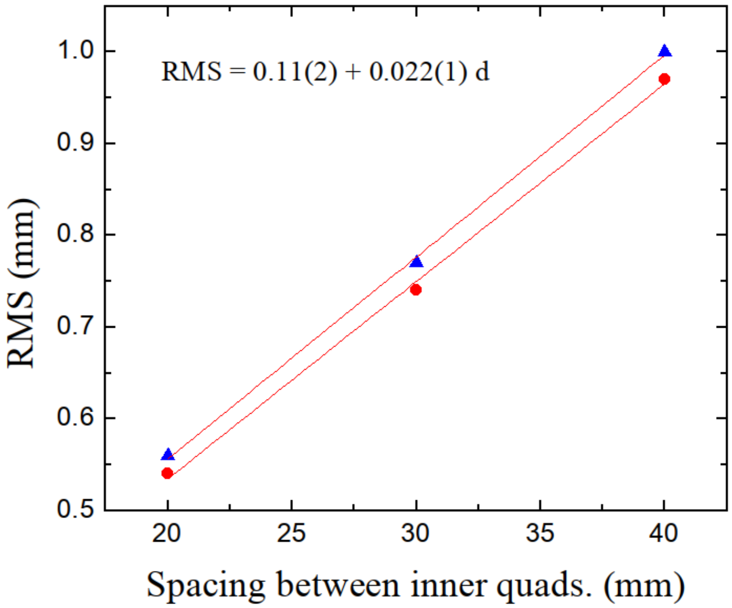
Deviation between vertex and actual hit



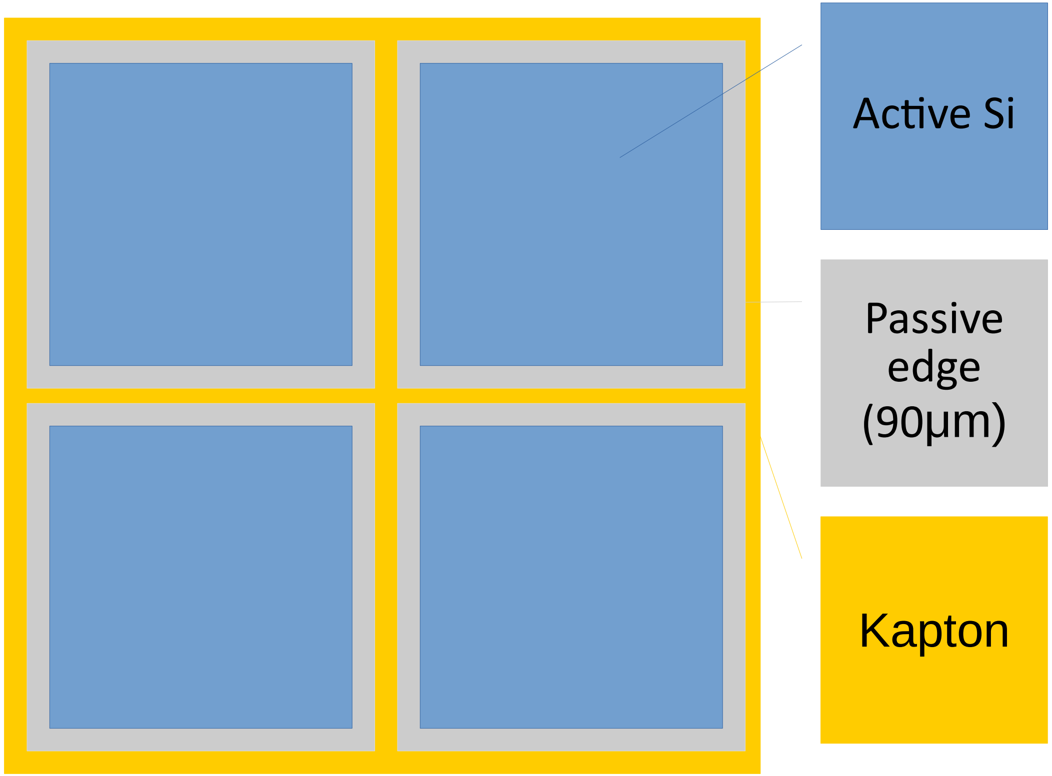
Vertex reconstruction, how far can we go?

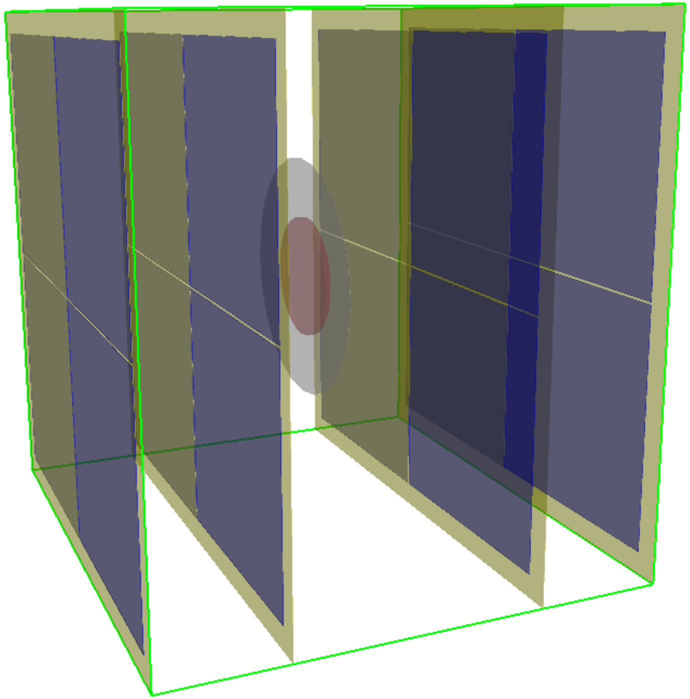


Infinitely sharp beam



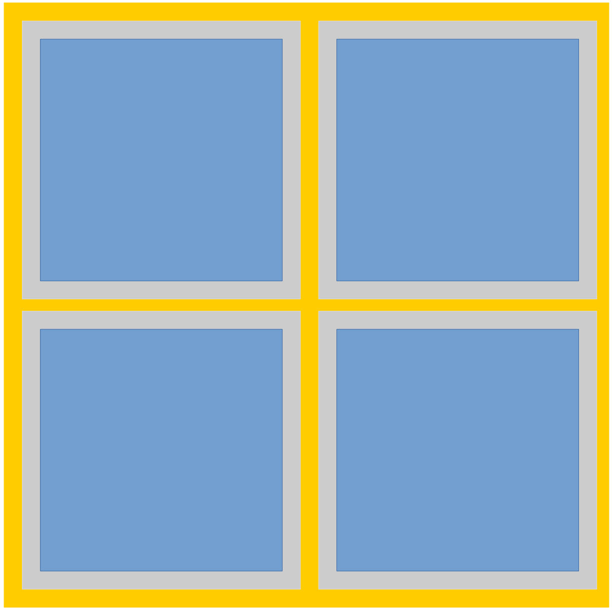
Simulation of realistic quads





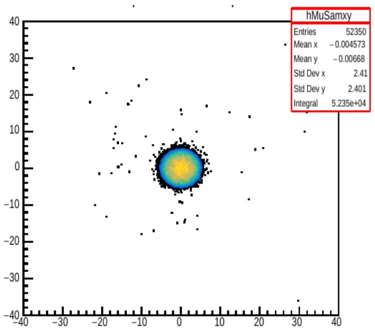
Simulation of realistic quads

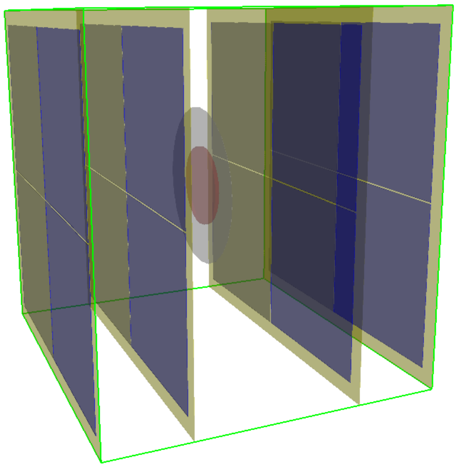
- Passive edge fixed at 90 μm.
- Spacing between the chips varied (0, 50, …, 250 μm).
- Kapton layer is 20 μm, Si layer is 50 μm.



The effect of the gaps visible with veto

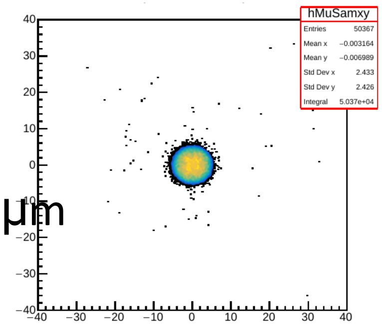
- Beam with 4mm $\sigma_{x,y}$
- No spacing
- No passive edge

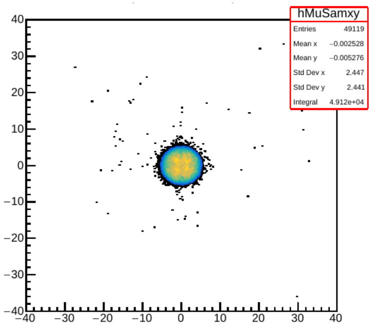


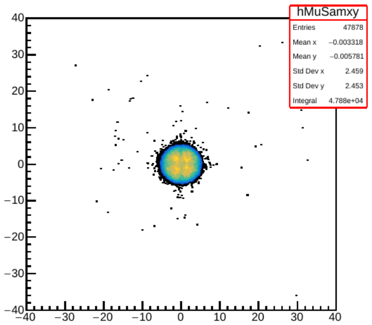


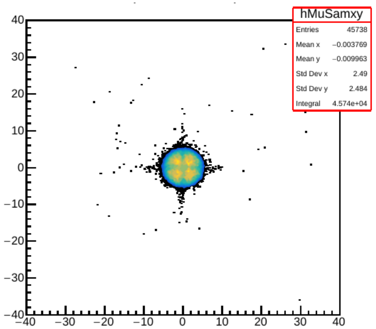
Beam with 4mm $\sigma_{x,y}$

Passive edge fixed at 90µm







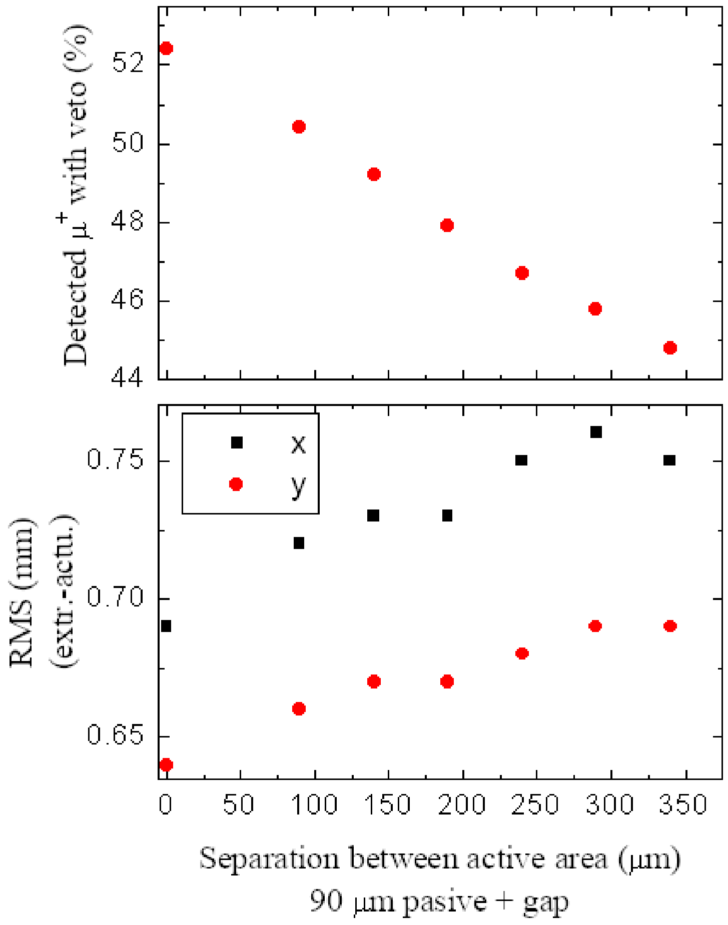


Spacing:

0 µm | 50 µm | 100 µm | 200 µm

What changes as a function of spacing

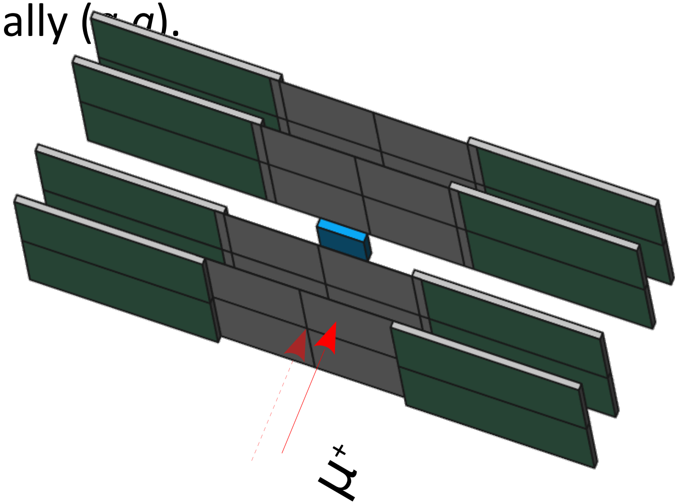
the gaps but mainly due the veto algorithm.
uction resolution, i.e. RMS of the difference between extrapolated

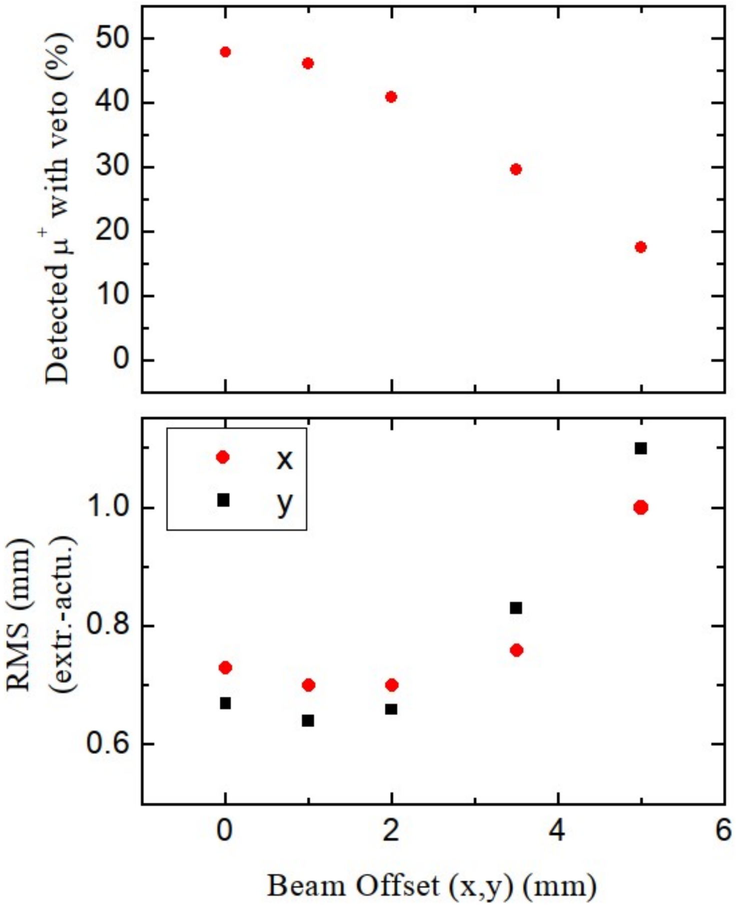


uon.

What if we offset the beam from sample

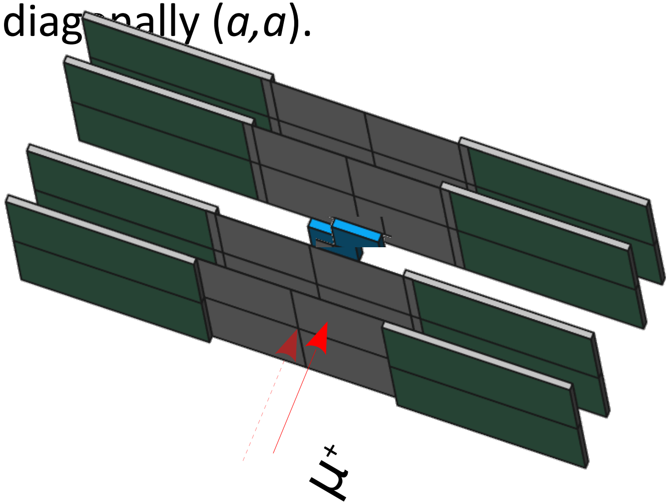
e region with passive edge fixed at 90µm. Spacing between pixels
beam offset diagonally (q,q).

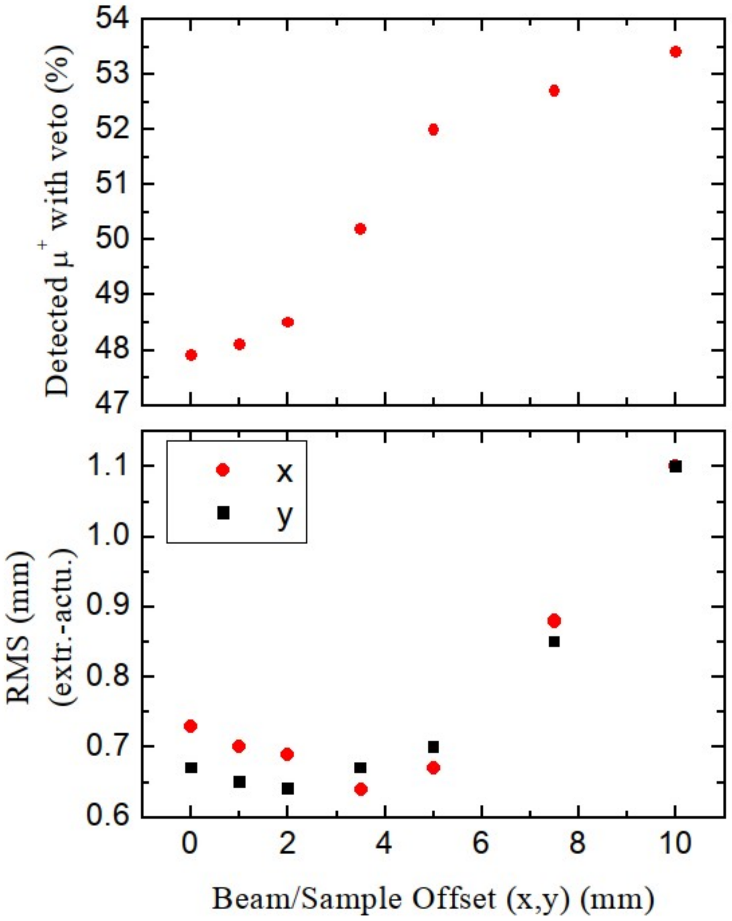




What if we offset the beam from sample

ve region with passive edge fixed at 90μm. Spacing between pixels
m and **Sample** offset diagonally (a,a).



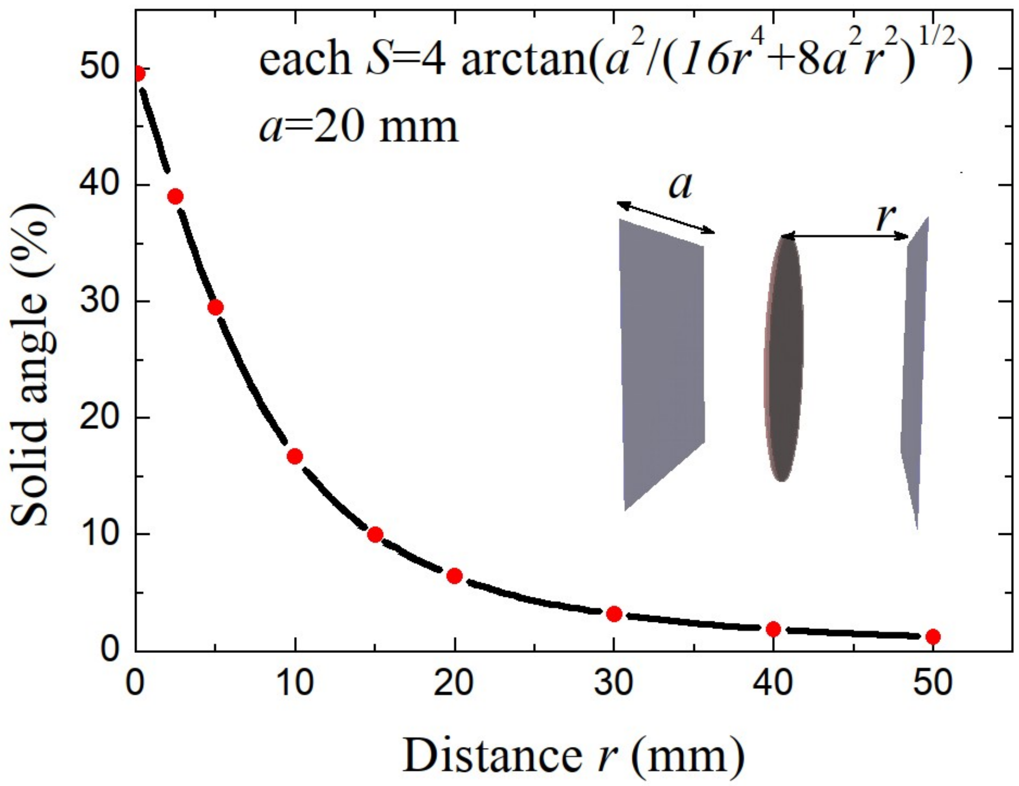


Solid Angle Calculation

Assuming Si Pixel detectors of 20x20 mm^2, placed 10 mm from the sample (center):

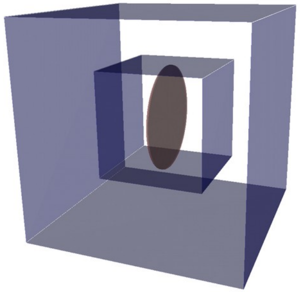
- The solid angle for each is 1/6
- A solid angle of 1/3 from the Forward/Backward set.
- The outer set should cover the same solid angle, i.e. 40x40 mm^2, placed 20 mm from the sample.

It is also possible double this by adding a Top/Down set as well, with the exact same geometry of the Forward/Backward

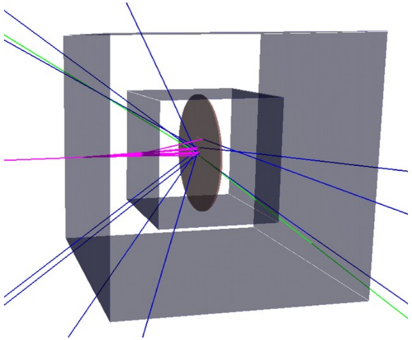


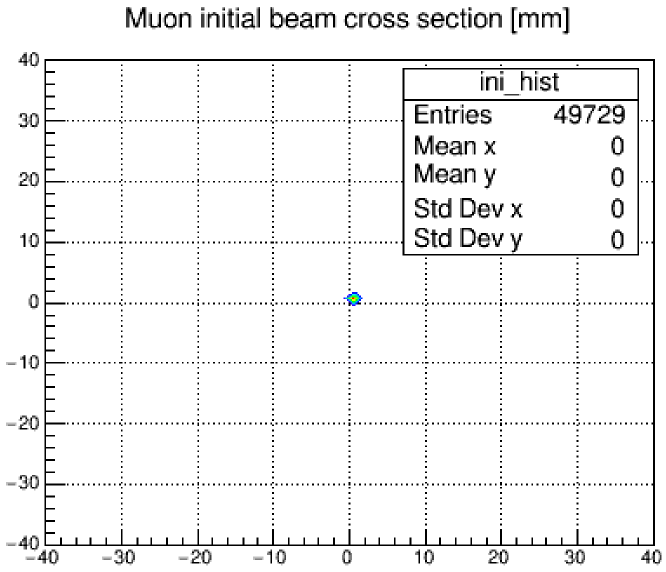
https://vixra.org/abs/2001.0603

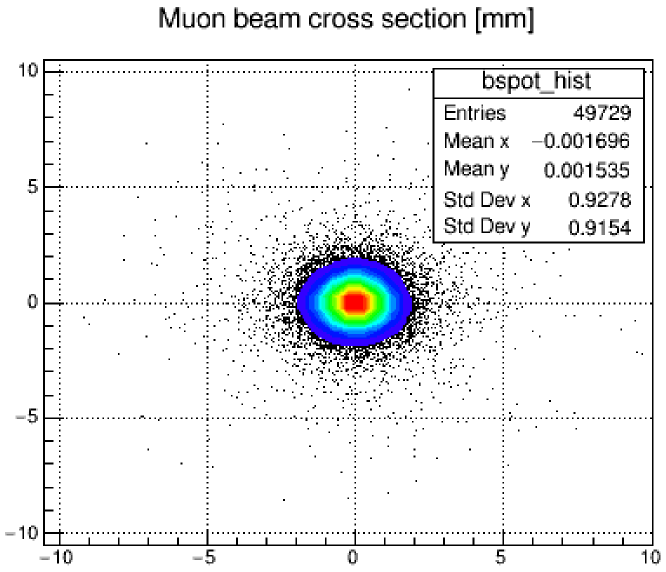
Scattering due to Outer/Inner Detectors



10 mm between target and inner set
10 mm between inner and outer set

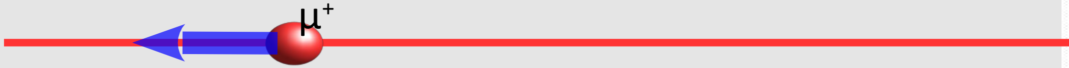


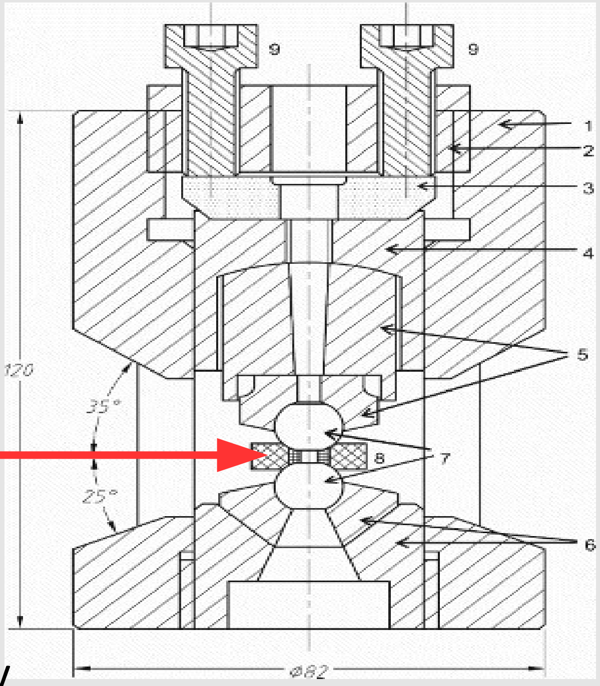




Microbeam for Small Samples…

Microbeam for
- Very small samples
- Extreme condition studies, e.g.,
- pressure up to 10 GPa using anvil cells (currently 3GPa).





- Scanning across samples to detect variation and homogeneity