A Silicon Pixel Tracker for future μSR Experiments

Enabling more precise investigation of magnetic and superconducting materials

BTTB 12 - Edinburgh

Lukas Mandok

On behalf of the HD-HVMAPS collaboration

Physikalisches Institut Heidelberg

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PAUL SCHERRER INSTITUT PSI

µSR Principle

Muon Spin **R**otation/**R**elaxation/**R**esonance

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Material Science Technique

Measure local magnetic fields

µSR Principle

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- Material Science Technique
- Measure local magnetic fields
- Battery materials
- Superconducting materials

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Measure local magnetic fields

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Implant spin polarized muons in sample material

µSR Principle

Muon Spin Rotation/**R**elaxation/**R**esonance

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Battery materials

Superconducting materials

Implant spin polarized muons in sample material

Muon spin evolves in internal and external magnetic field

µSR Principle

Muon **S**pin **R**otation/**R**elaxation/**R**esonance

- Material Science Technique
- Measure local magnetic fields
- Battery materials
- Superconducting materials

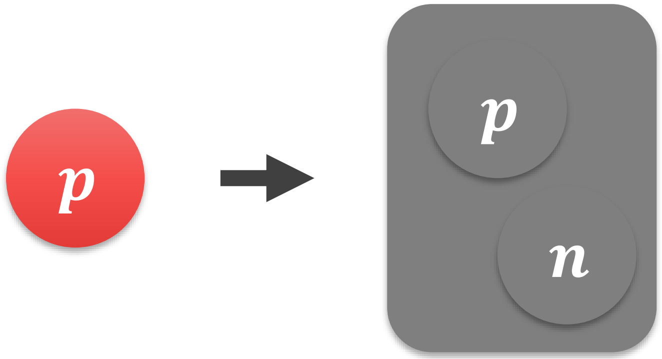
1. Implant spin polarized muons in sample material
2. Muon spin evolves in internal and external magnetic field
3. Measure anisotropic decay to positrons

µSR Method

µSR Method

$590\ \mathrm{MeV}$
Proton
beam
@PSI

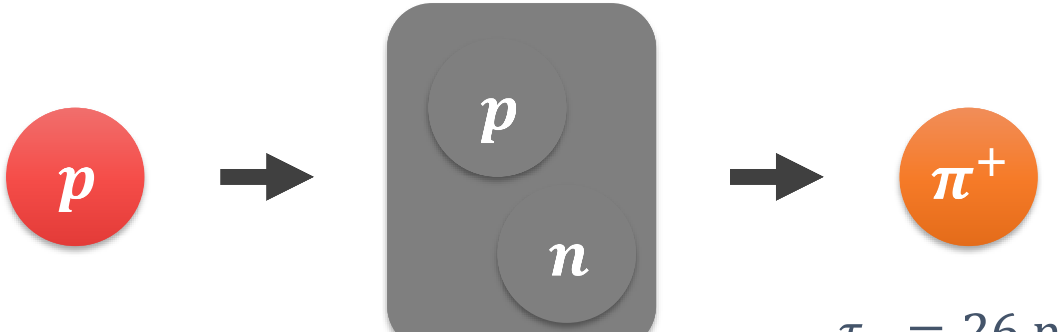
µSR Method



590 MeV
Proton beam @PSI

C/Be target

µSR Method



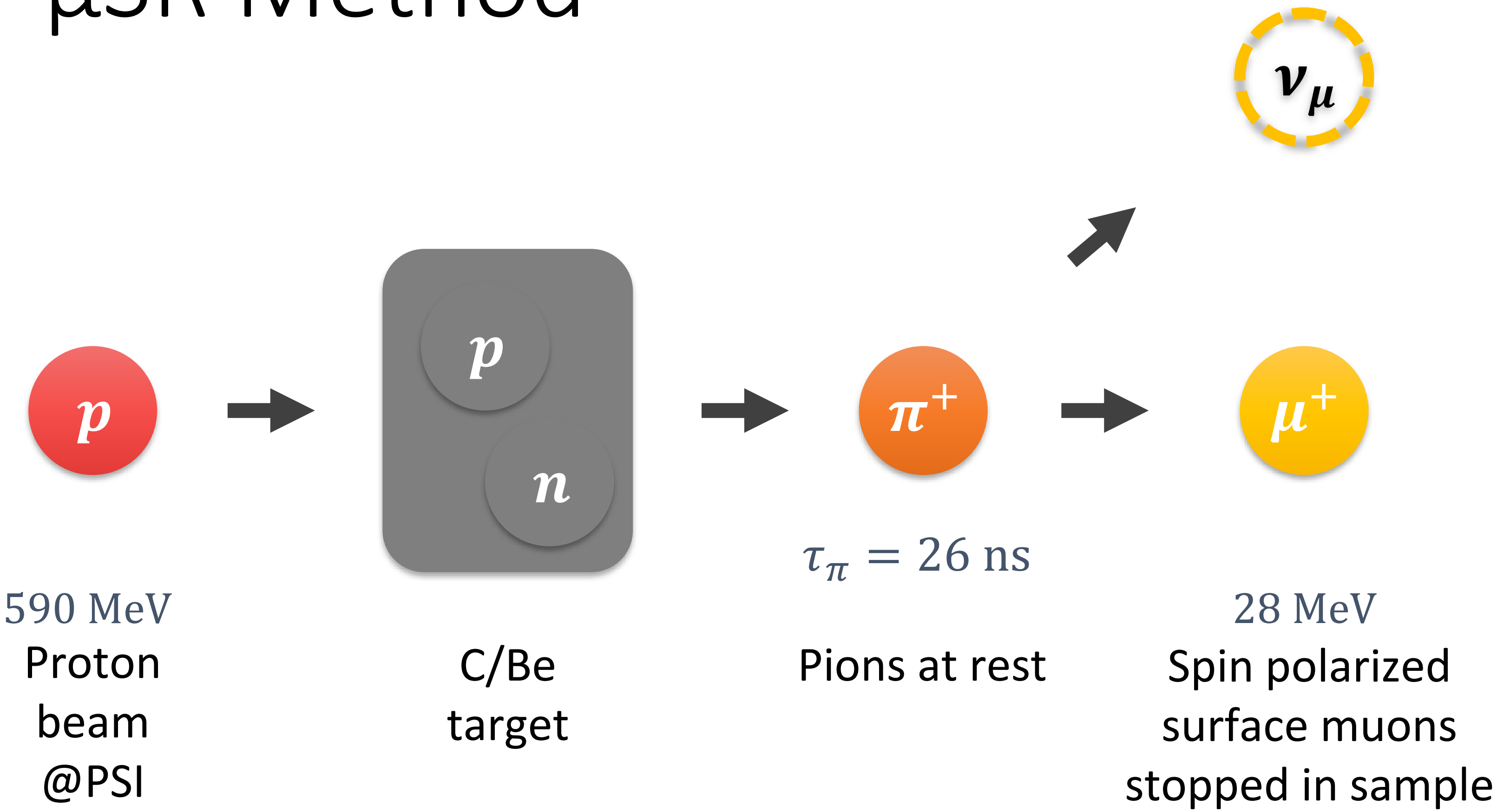
$\tau_\pi = 26\ \mathrm{ns}$

590 MeV
Proton beam @PSI

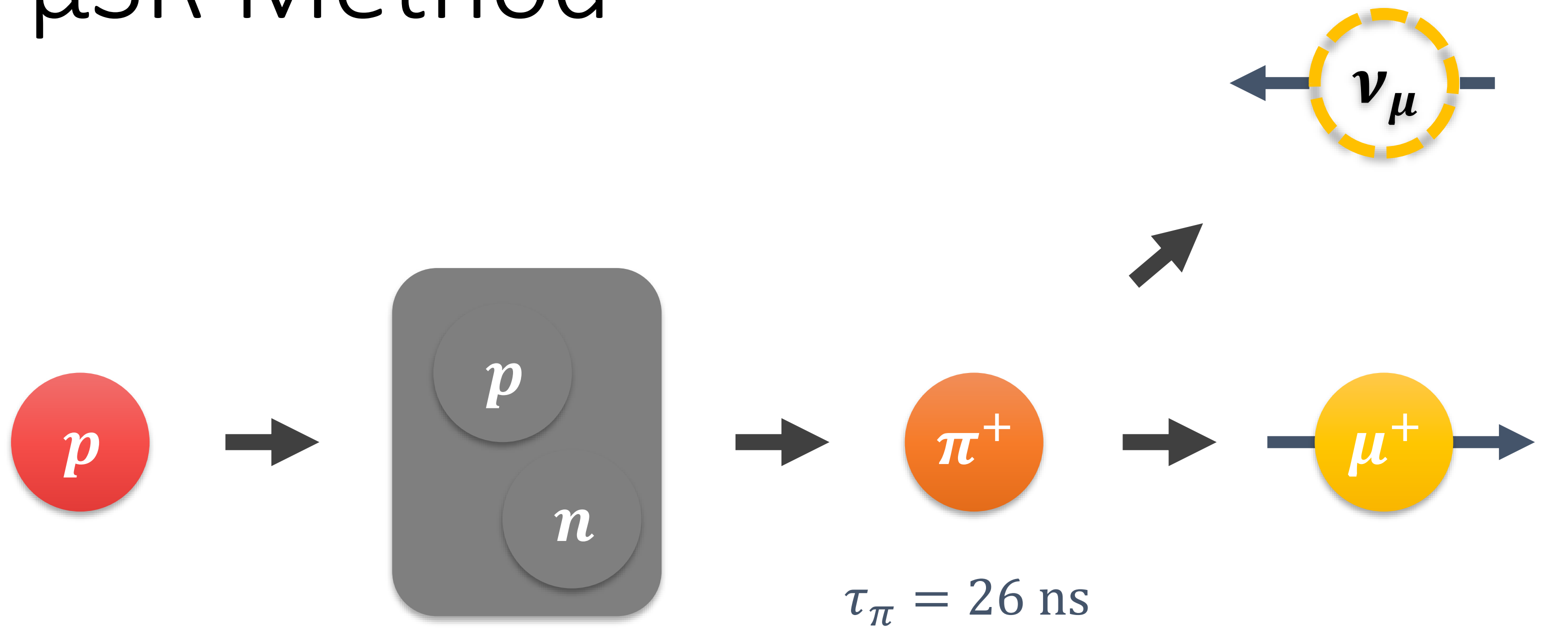
C/Be target

Pions at rest

µSR Method


ν_μ
p
p
n
π^+
μ^+
$\tau_\pi = 26\ \mathrm{ns}$
590 MeV
Proton beam @PSI
C/Be target
Pions at rest
28 MeV
Spin polarized surface muons stopped in sample

µSR Method



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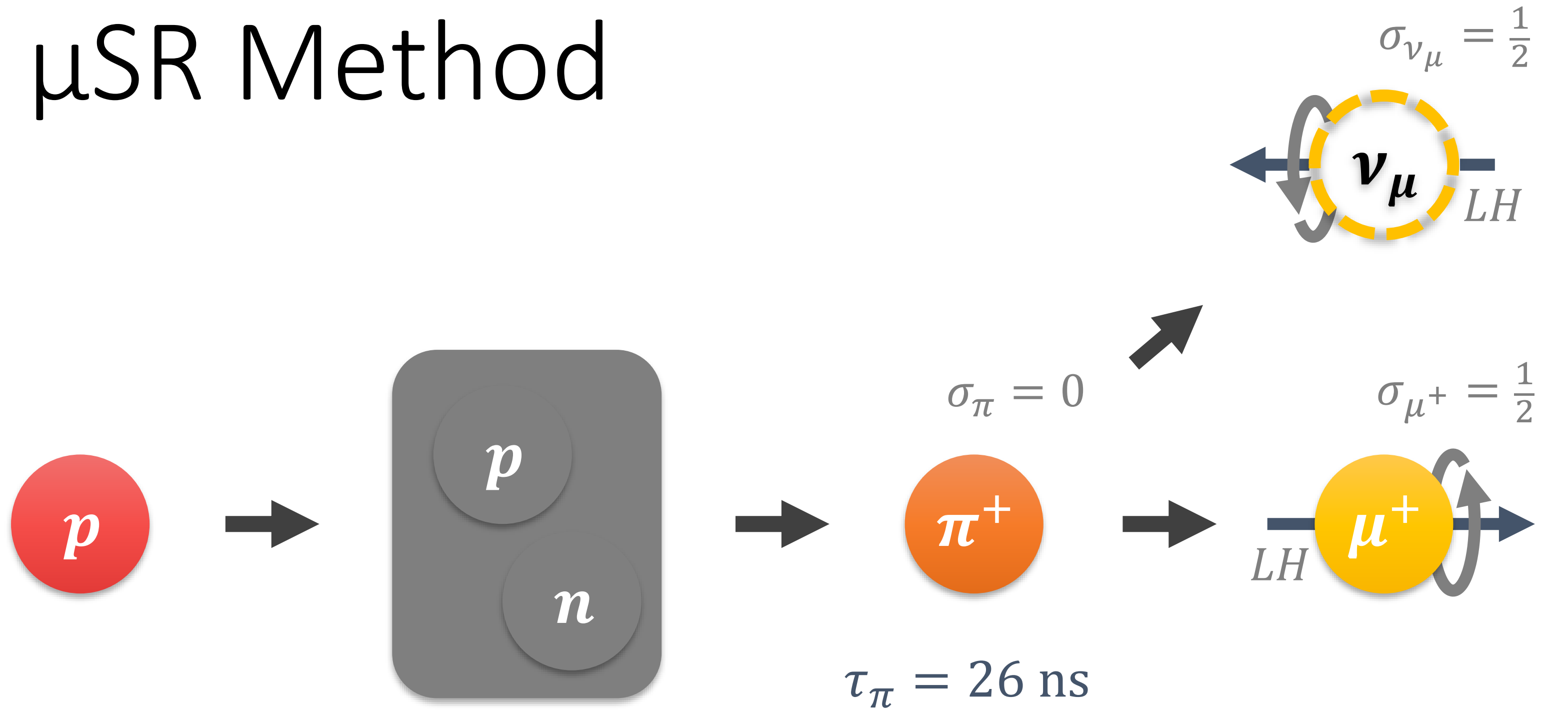

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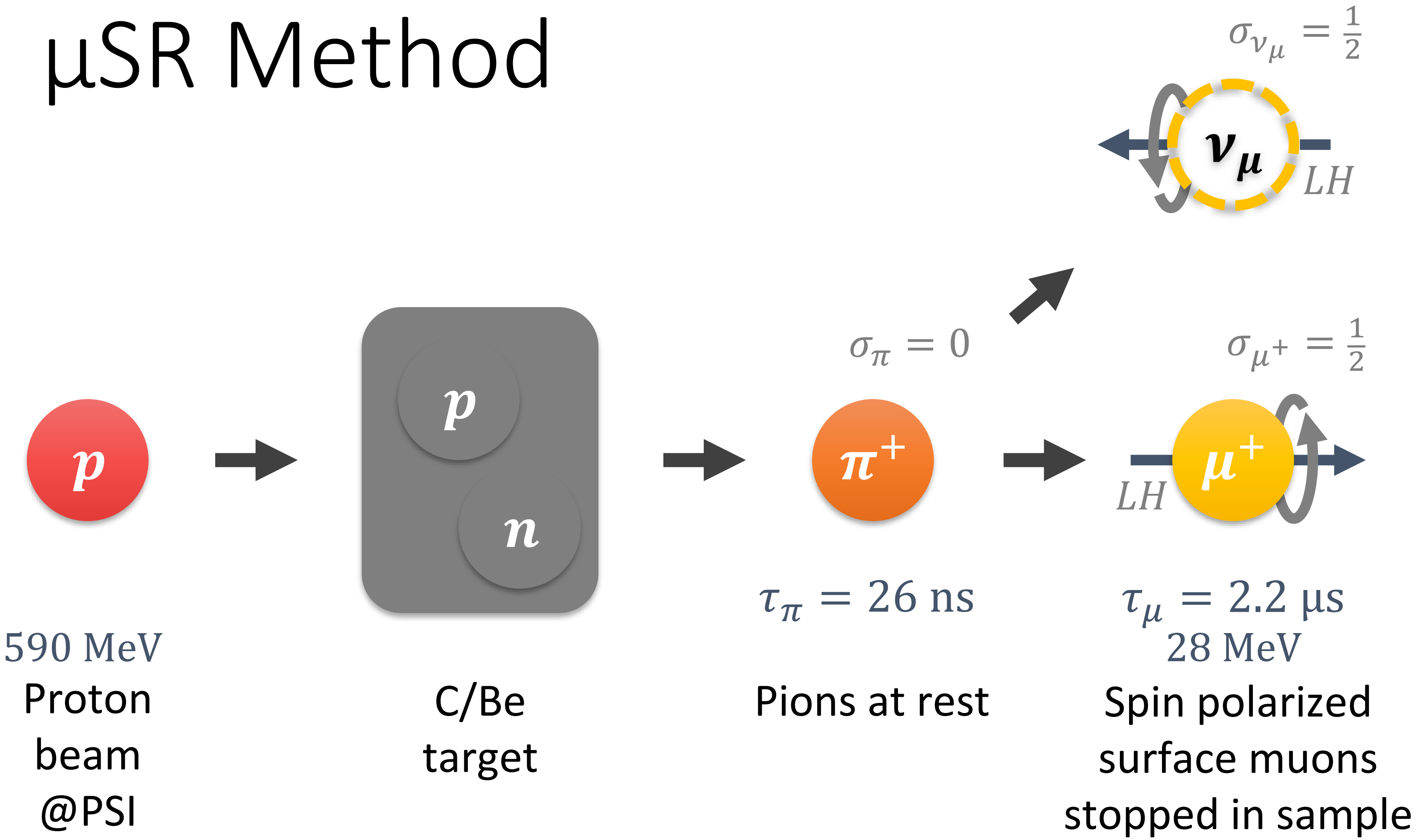
$\sigma_{\nu_\mu} = \frac{1}{2}$
ν_μ
LH
p
p
n
$\sigma_\pi = 0$
π^+
$\sigma_{\mu^+} = \frac{1}{2}$
μ^+
LH
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$\tau_\mu = 2.2\ \mu\mathrm{s}$
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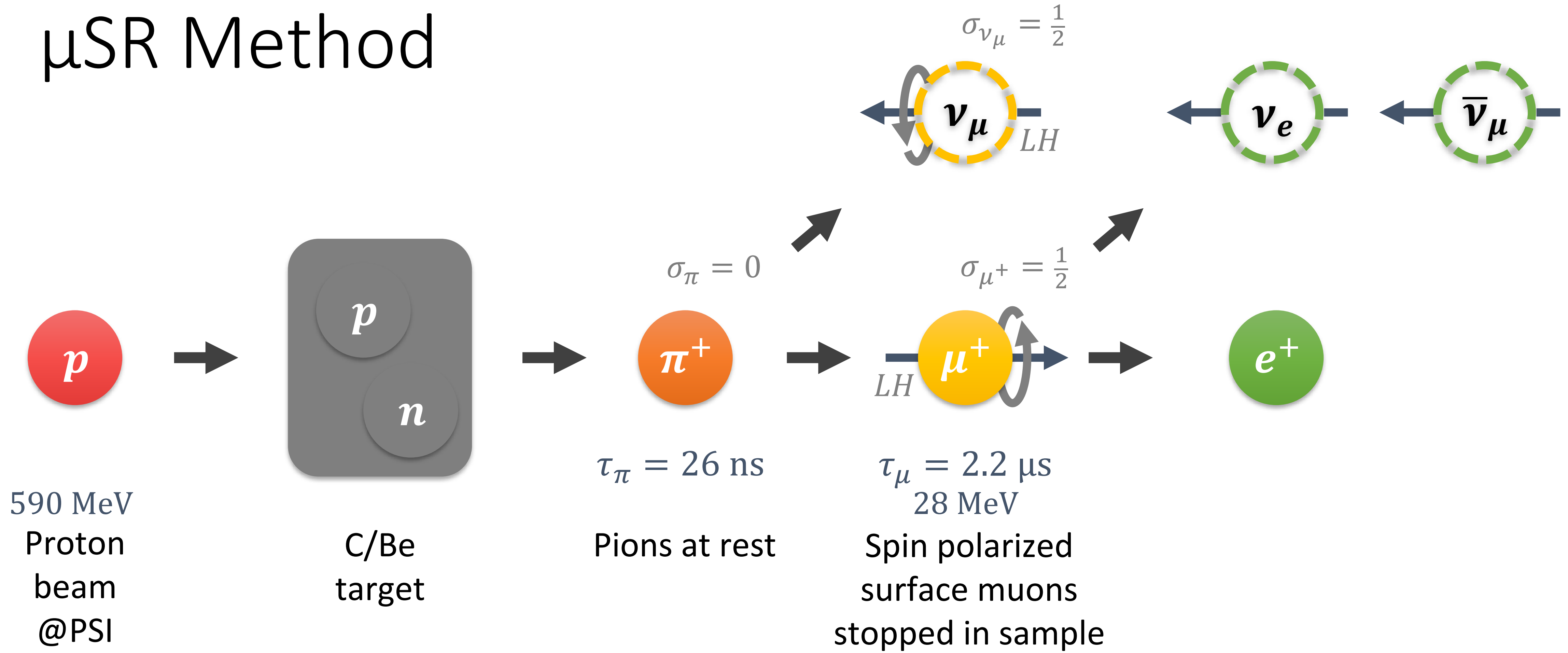

$\sigma_{\nu_\mu} = \frac{1}{2}$
ν_μ
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ν_e
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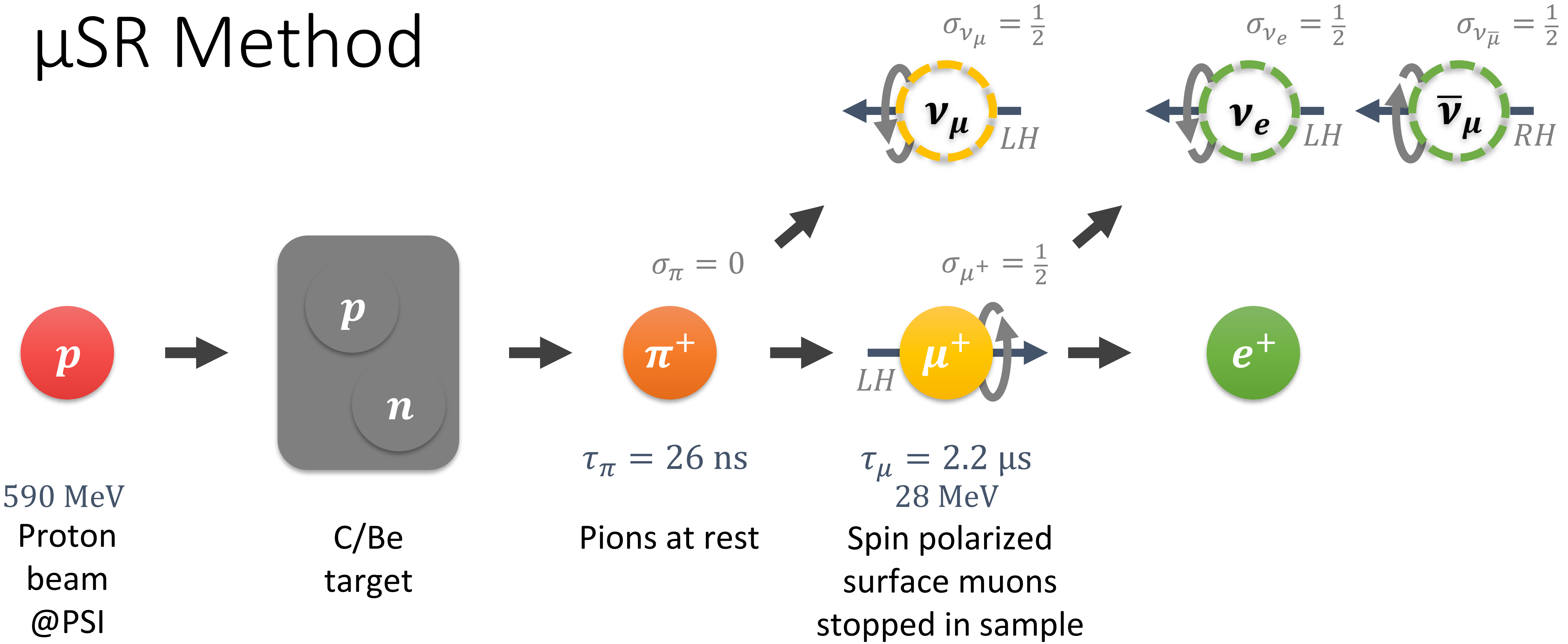

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LH
ν_e
LH
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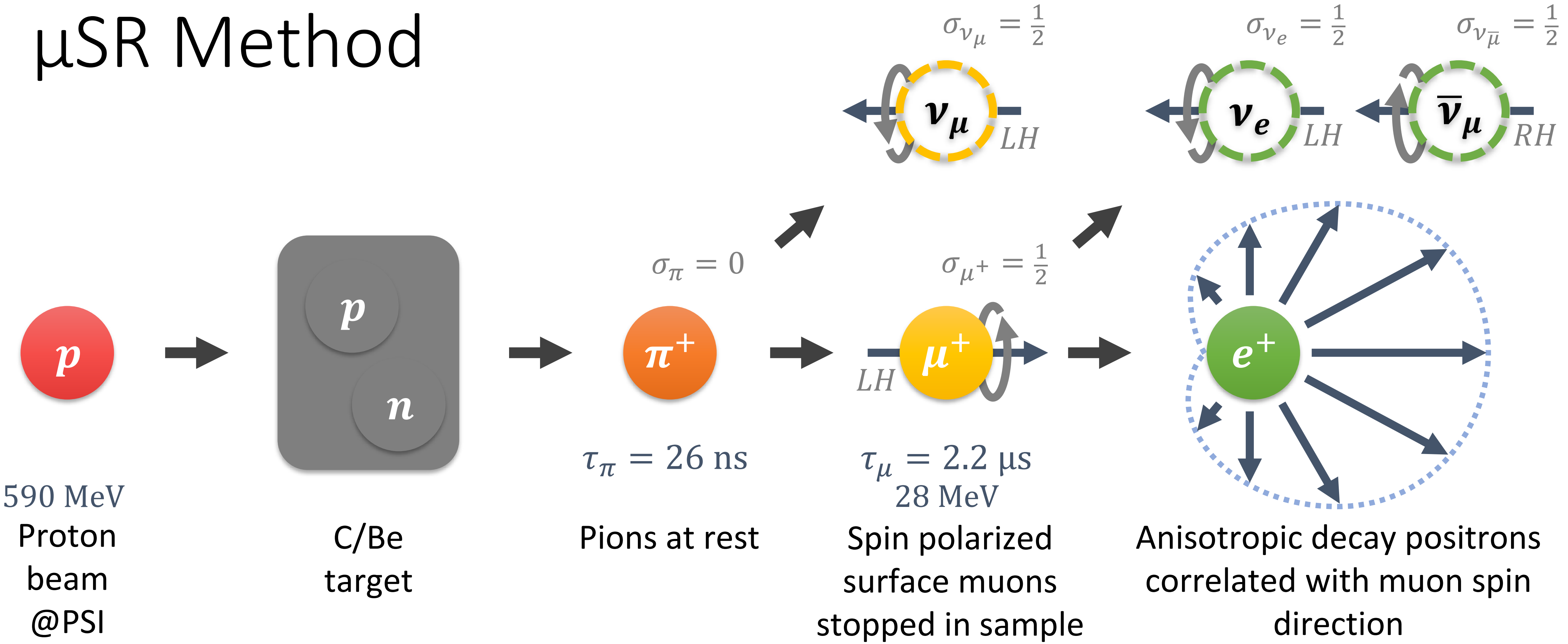

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Anisotropic decay positrons correlated with muon spin direction

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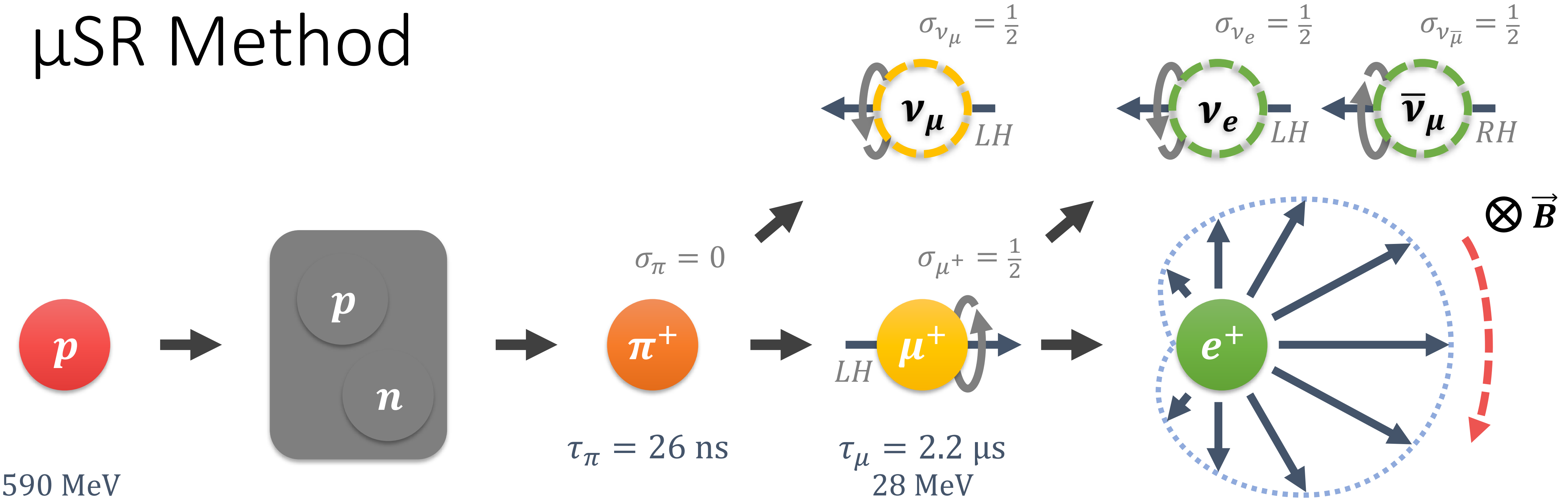

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Pions at rest

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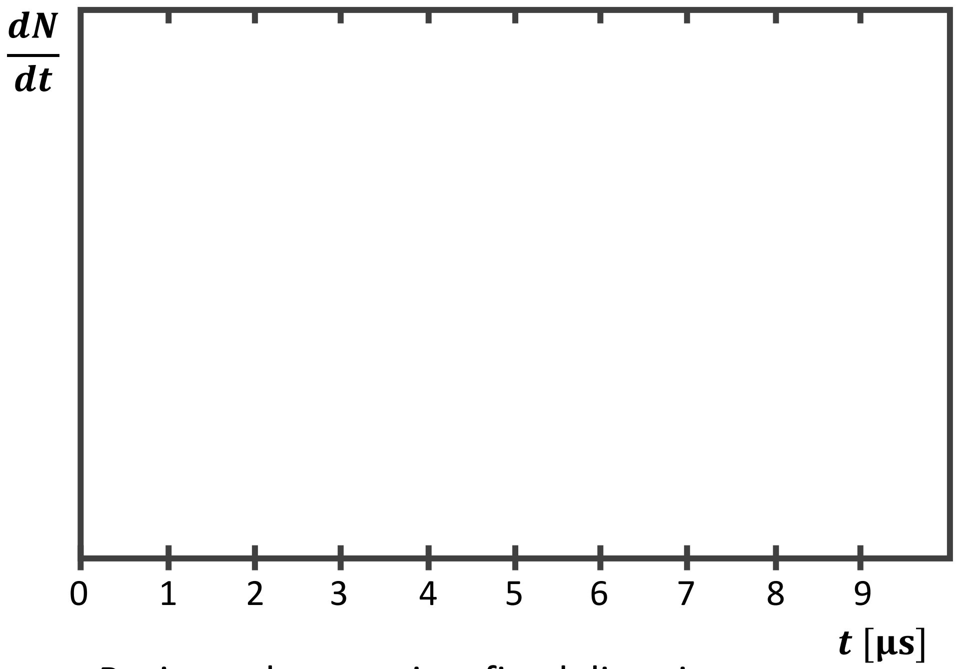
Anisotropic decay positrons correlated with muon spin direction

Spin precession

µSR Signal

Positron rate: $N(t)/dt = B_0 + N_0 \cdot \exp\left(-t/\tau_\mu\right) \cdot \left[1 + A_0 G_\perp(t)\, cos\left(\bar{\omega}_\mu t + \phi\right)\right]$

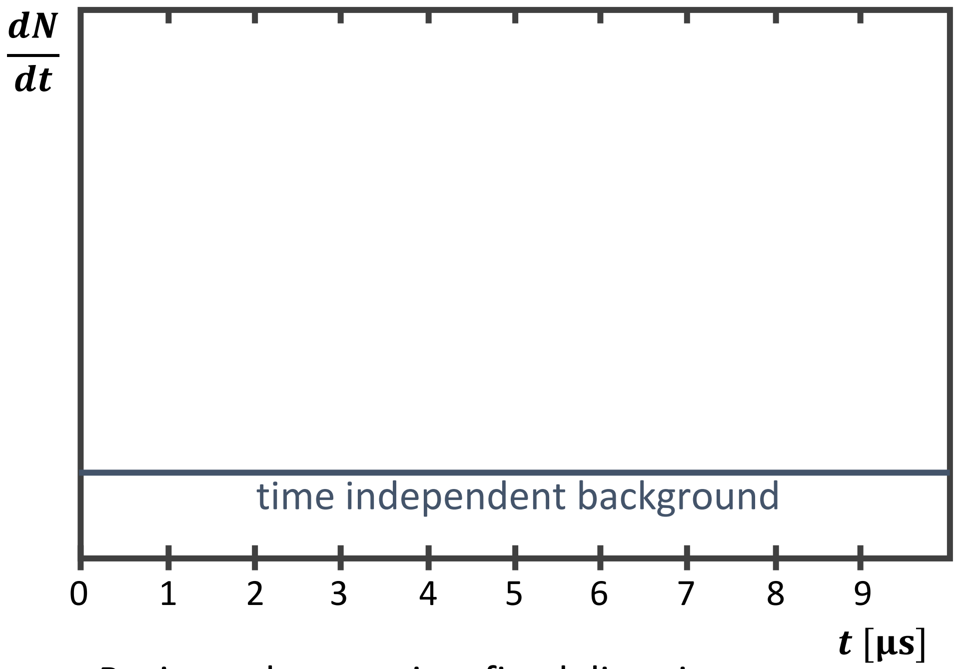


Positron detector in a fixed direction

µSR Signal

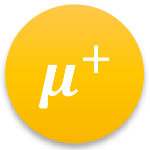
Positron rate: $N(t)/dt = \boldsymbol{B_0} + N_0 \cdot \exp(-t/\tau_\mu) \cdot \left[1 + A_0 G_\perp(t)\, cos(\bar{\omega}_\mu t + \phi)\right]$

Background



Positron detector in a fixed direction

Positron detector
$N(t)/dt$



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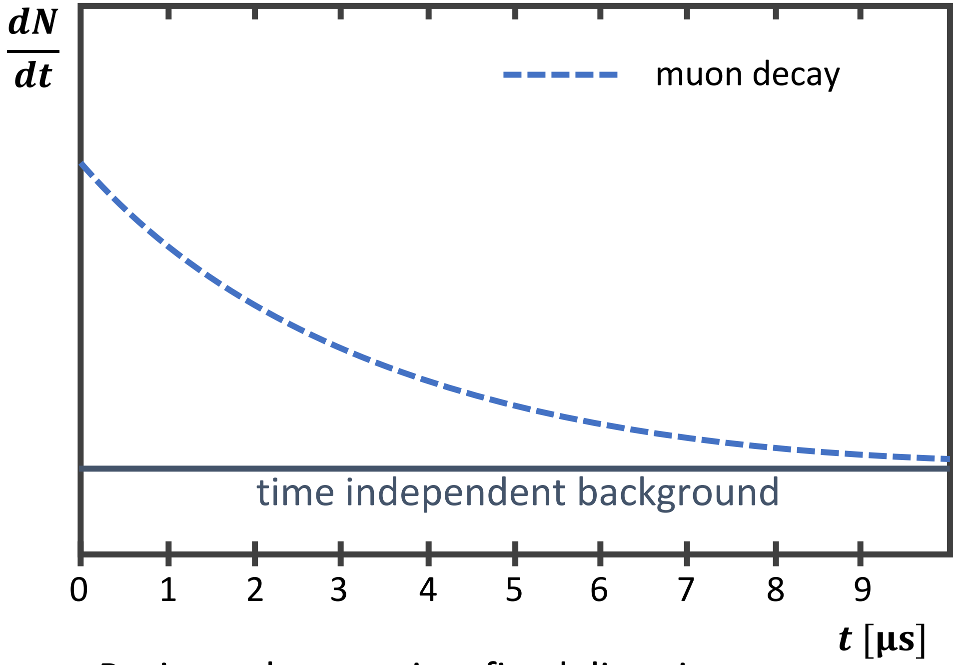
Positron rate: $$N(t)/dt = \underbrace{B_0}_{\textbf{Background}} + \underbrace{N_0 \cdot \exp(-t/\boldsymbol{\tau_\mu})}_{\text{Exponential muon } \textbf{decay}} \cdot \left[1 + A_0 G_\perp(t)\, cos(\bar{\omega}_\mu t + \phi)\right]$$



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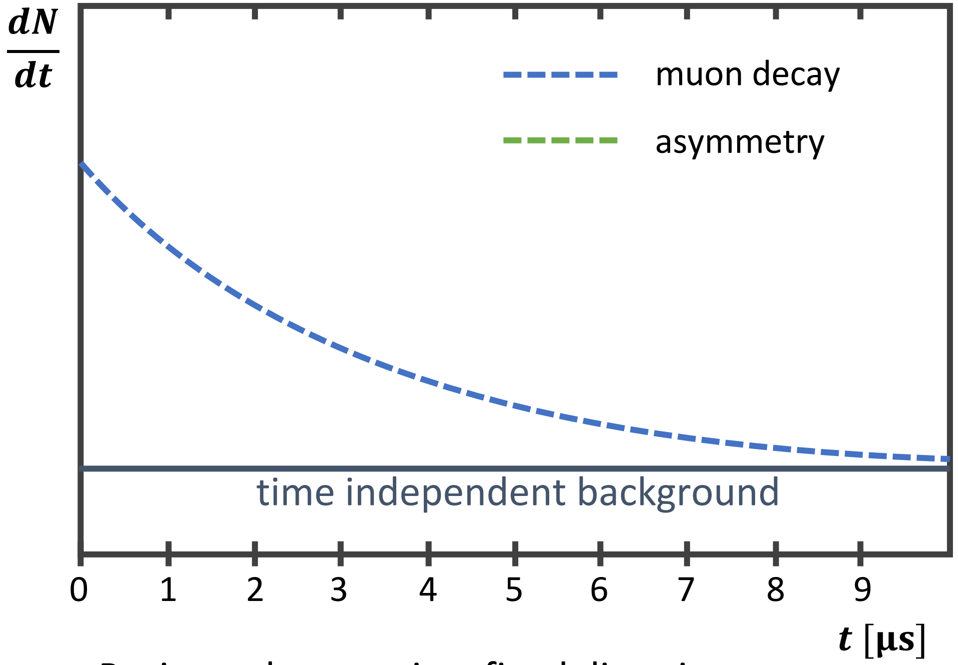
Background

Intrinsic asymmetry parameter of weak decay



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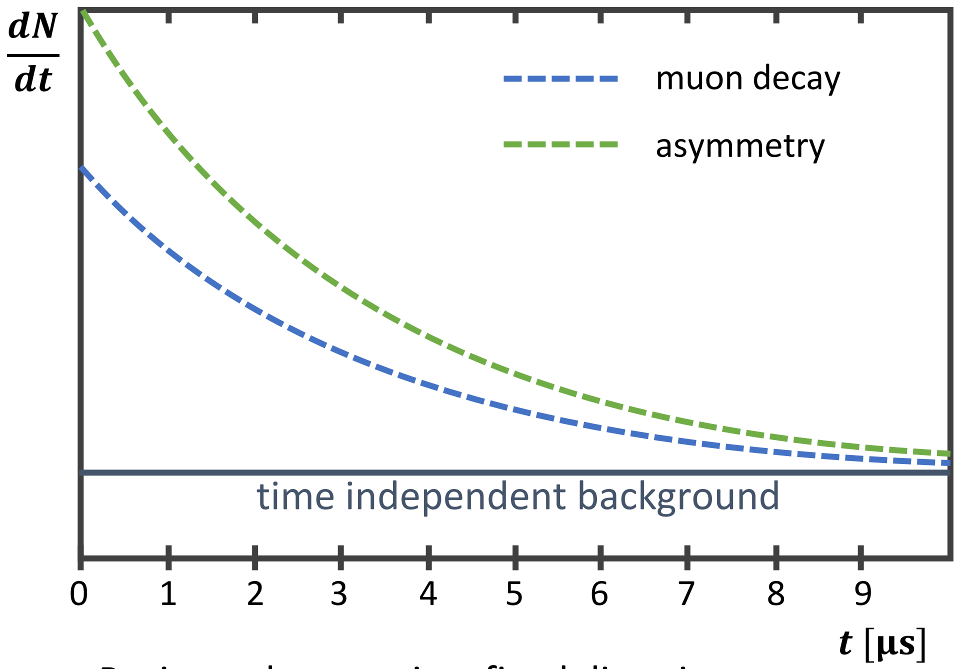
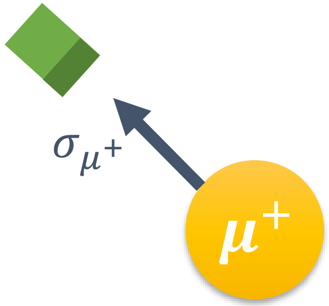
Exponential muon **decay**

Intrinsic asymmetry parameter of weak decay



Positron detector in a fixed direction

Positron detector
$N(t)/dt$



μSR Signal

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Intrinsic asymmetry parameter of weak decay

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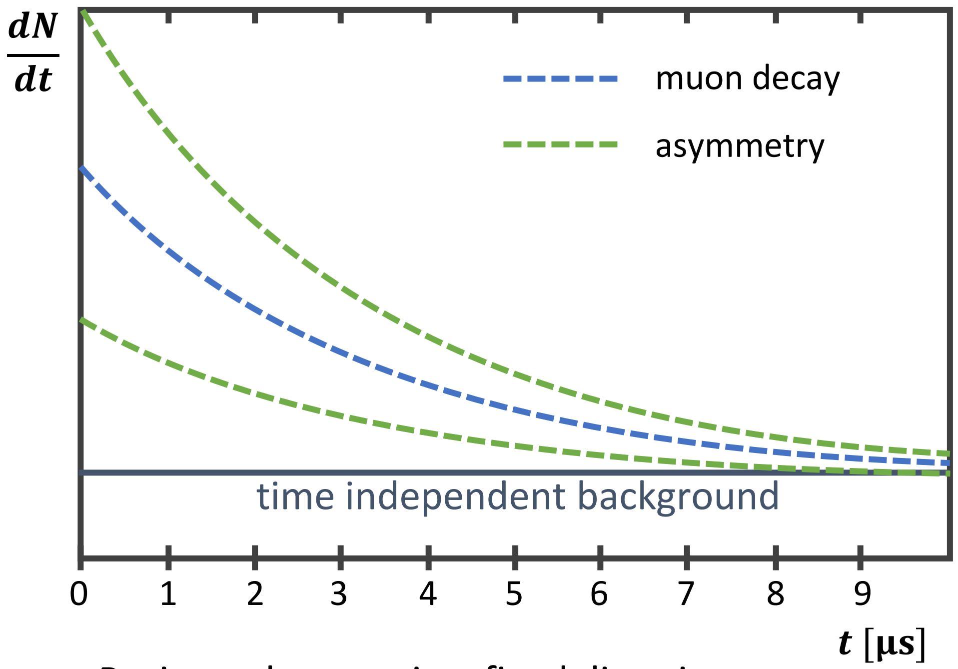
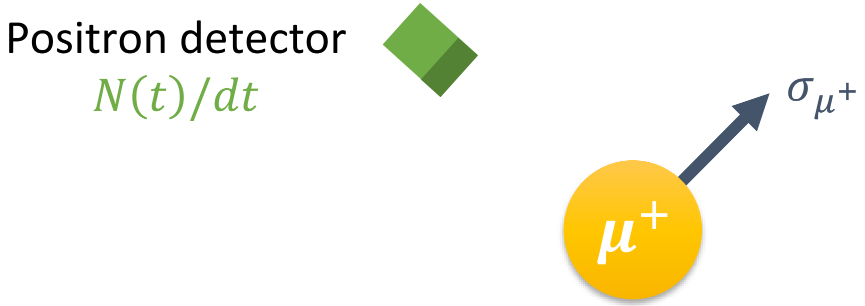


Positron detector in a fixed direction



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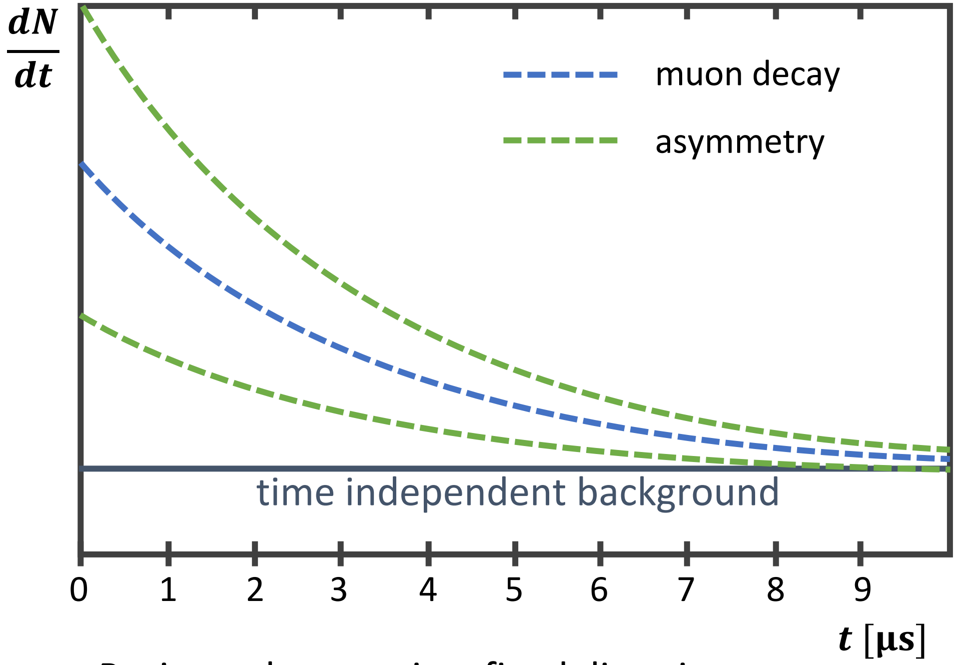
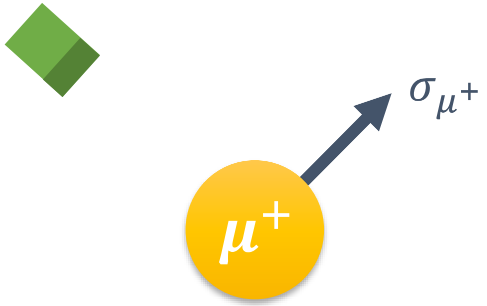
Exponential muon **decay**

Relaxation function of temporal decrease of the polarization degree



Positron detector in a fixed direction

Positron detector
$N(t)/dt$



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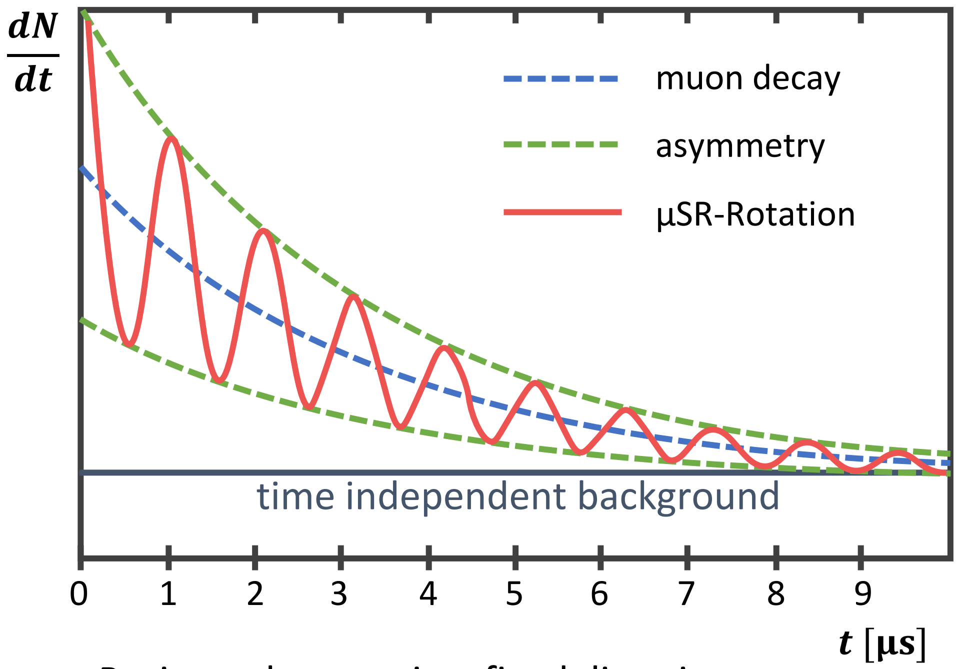
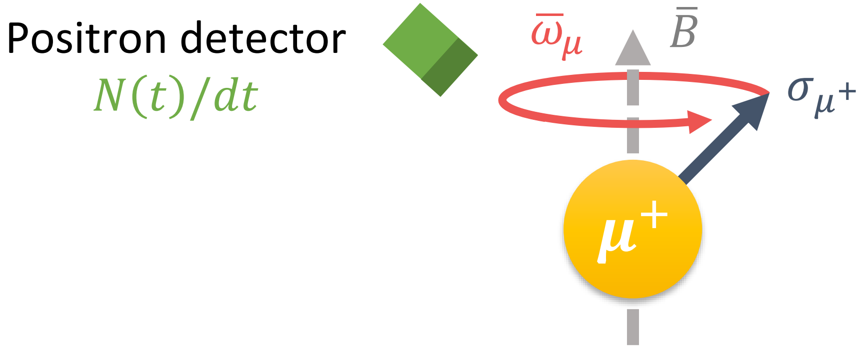
Relaxation function of temporal decrease of the polarization degree

Angle between positron and muon spin direction

Larmor frequency of muon spin precession: $\overline{\omega}_\mu = \gamma_\mu \cdot (B_{ext} + \langle B_{int} \rangle)$



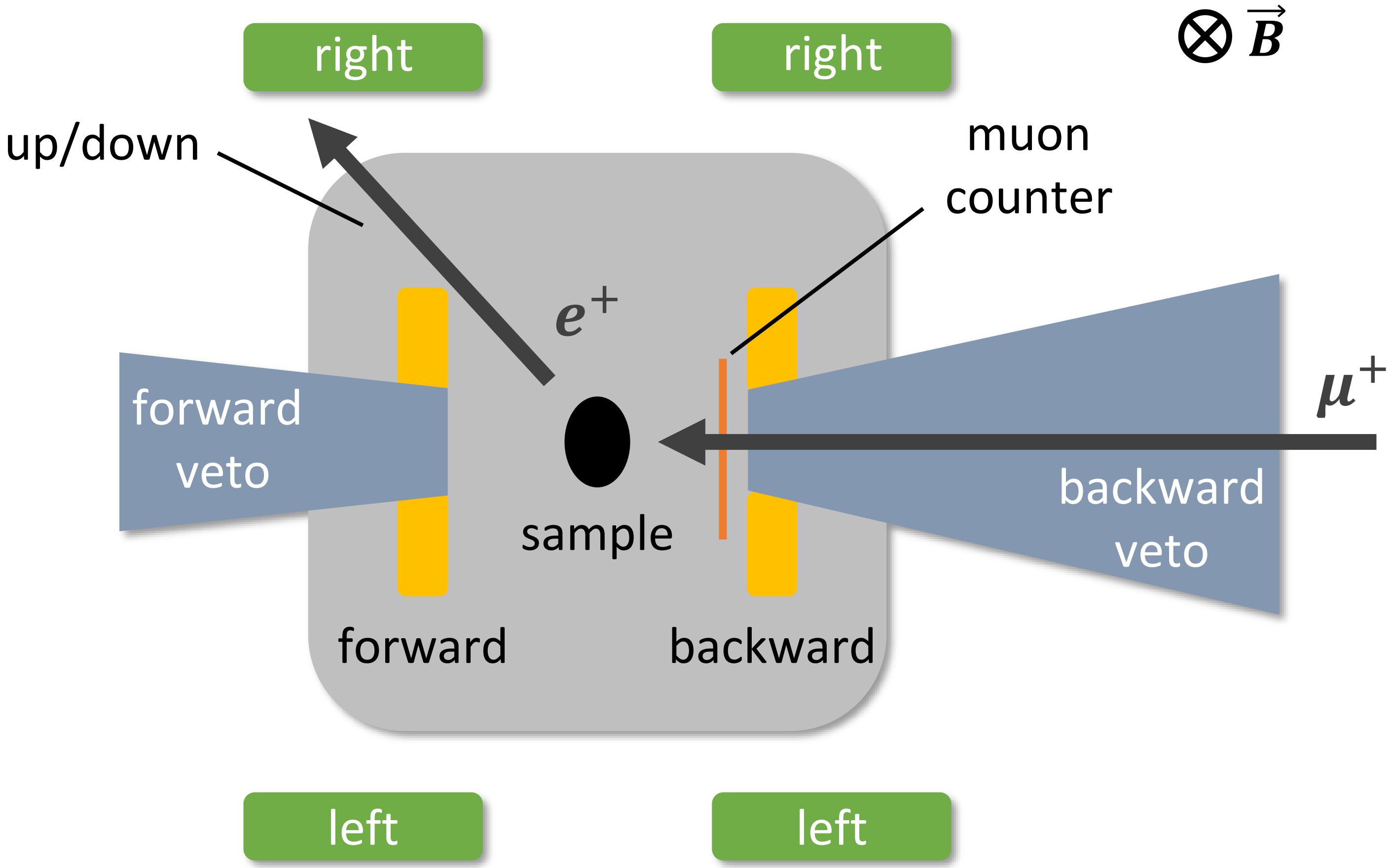
Positron detector in a fixed direction



Current Generation

Scintillator-based Detector

top view



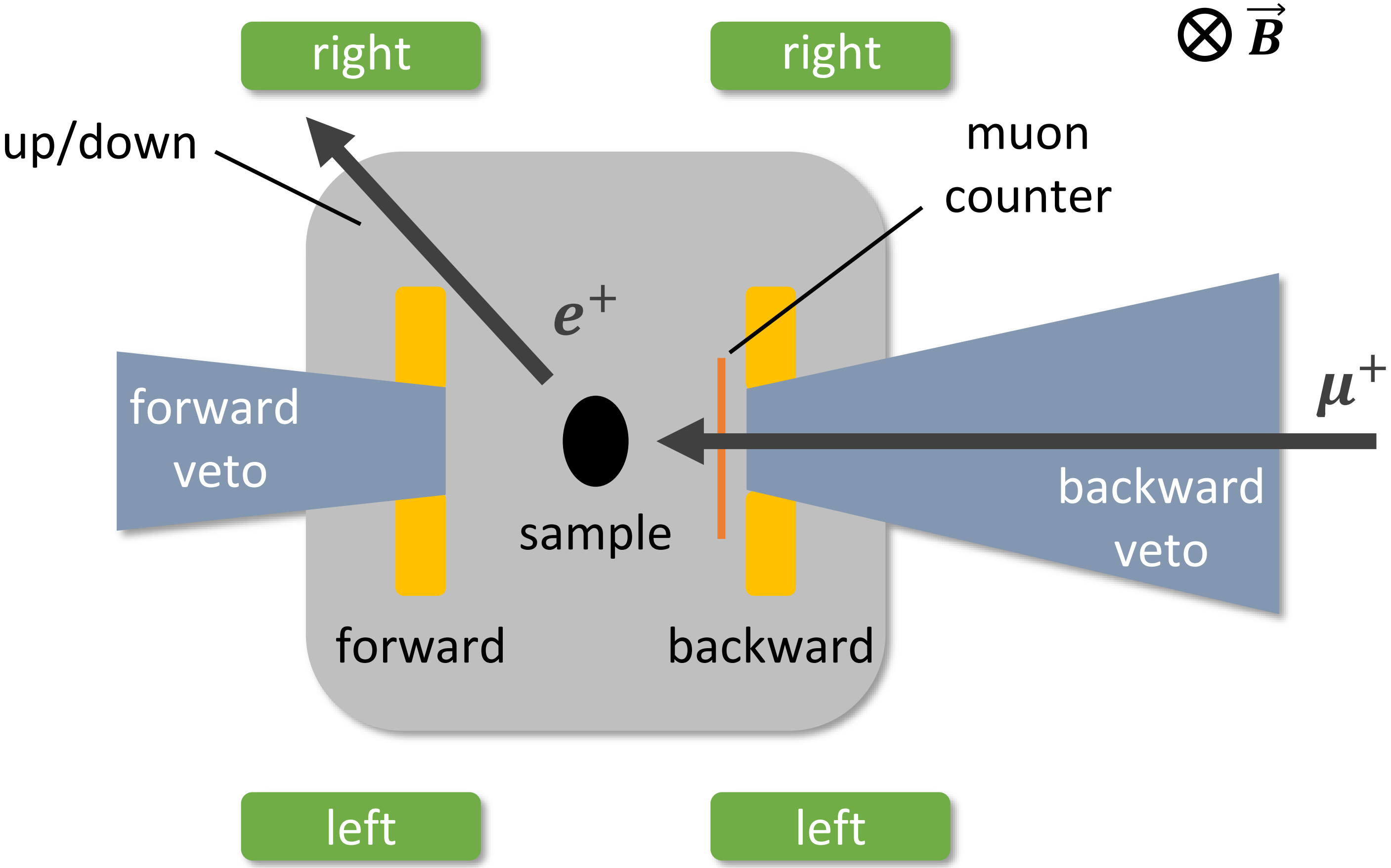
Adapted from: General Purpose Surface-Muon Instrument (GPS). User Guide.

Current Generation
Scintillator-based Detector

Measure:

- Time of Arrival of μ^+ and e^+
- Temporal asymmetry between forward and backward signals

top view



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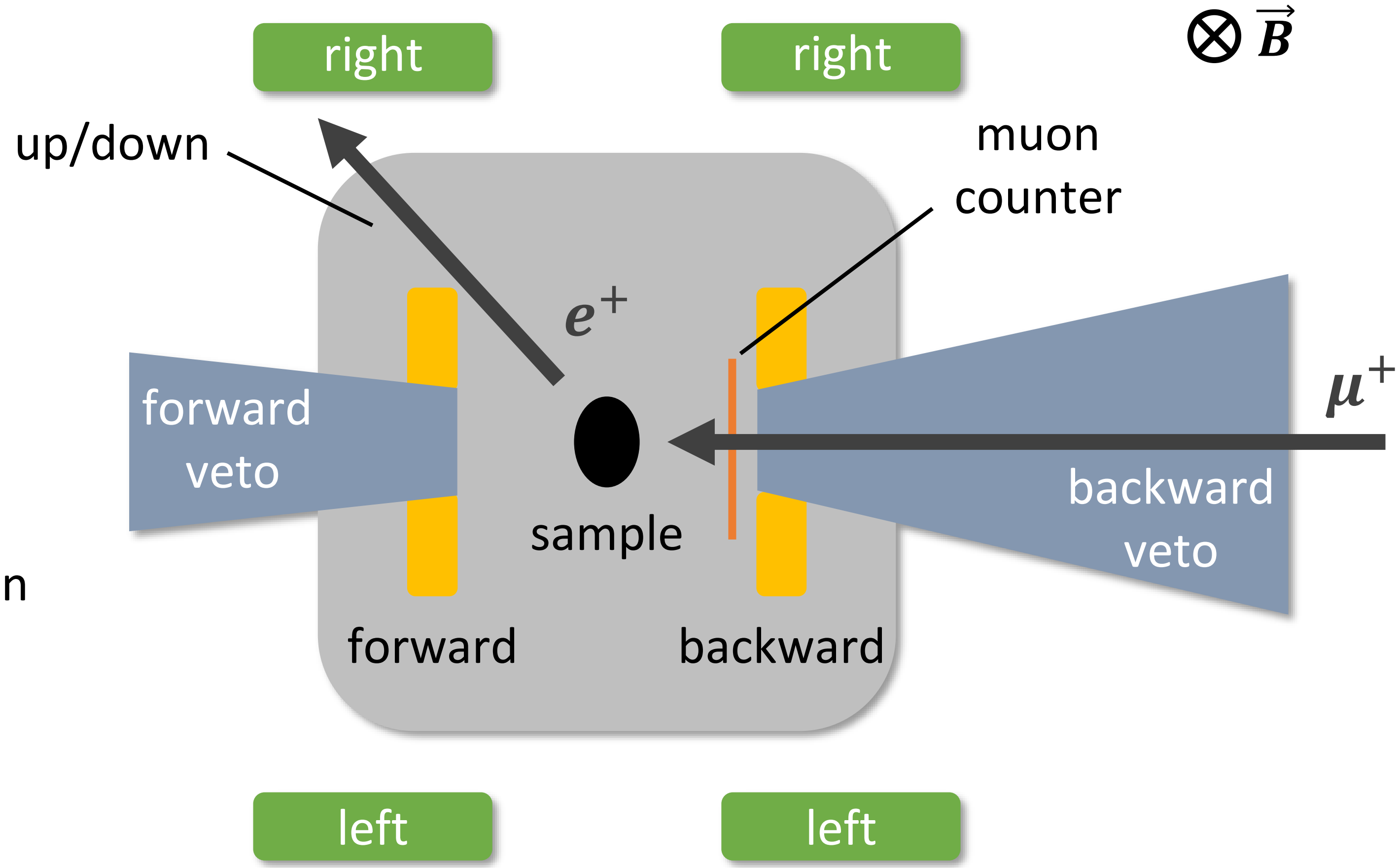

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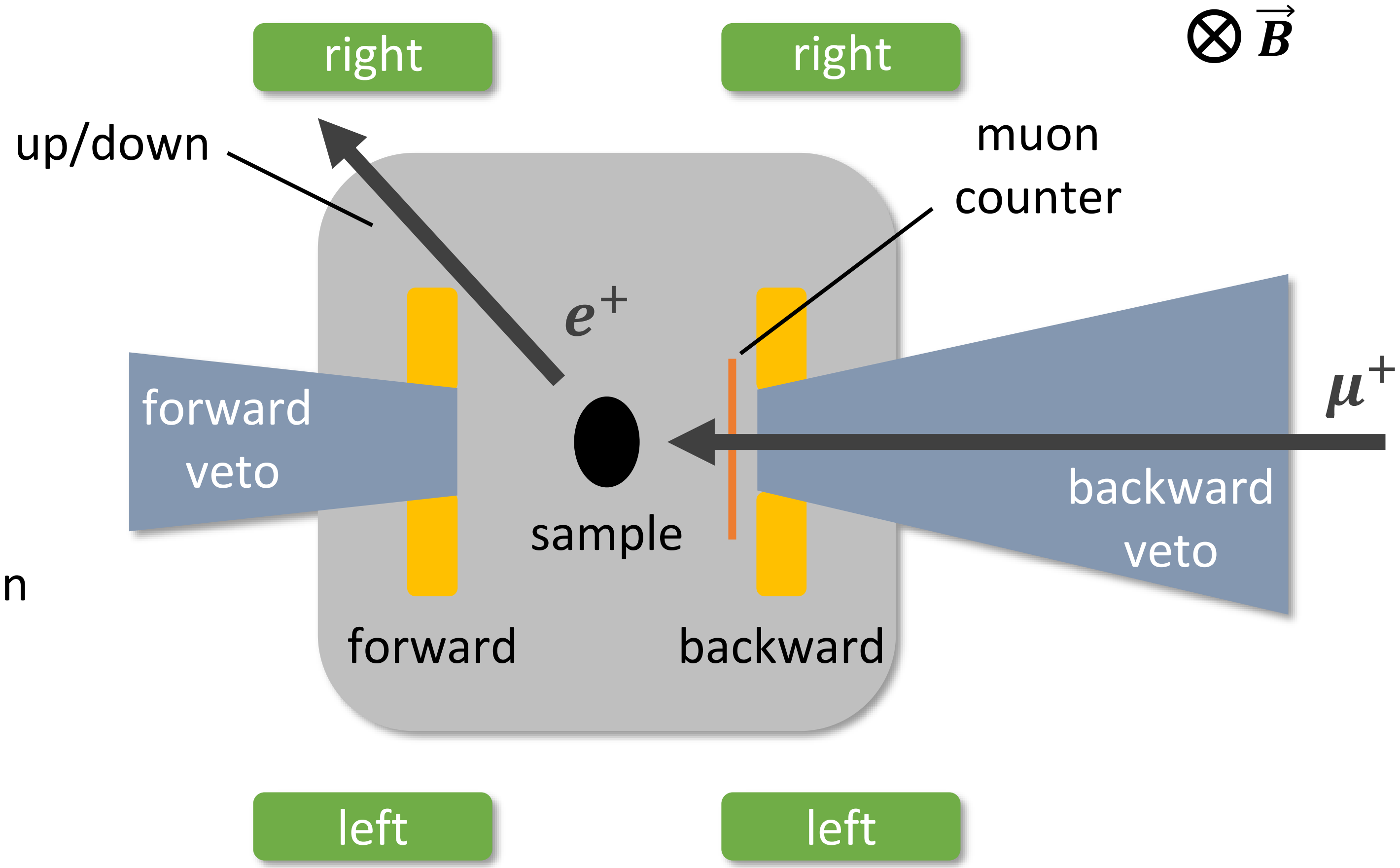
- Rate limitation
  - Maximal 1 muon per time frame
  - Limited observation time

top view



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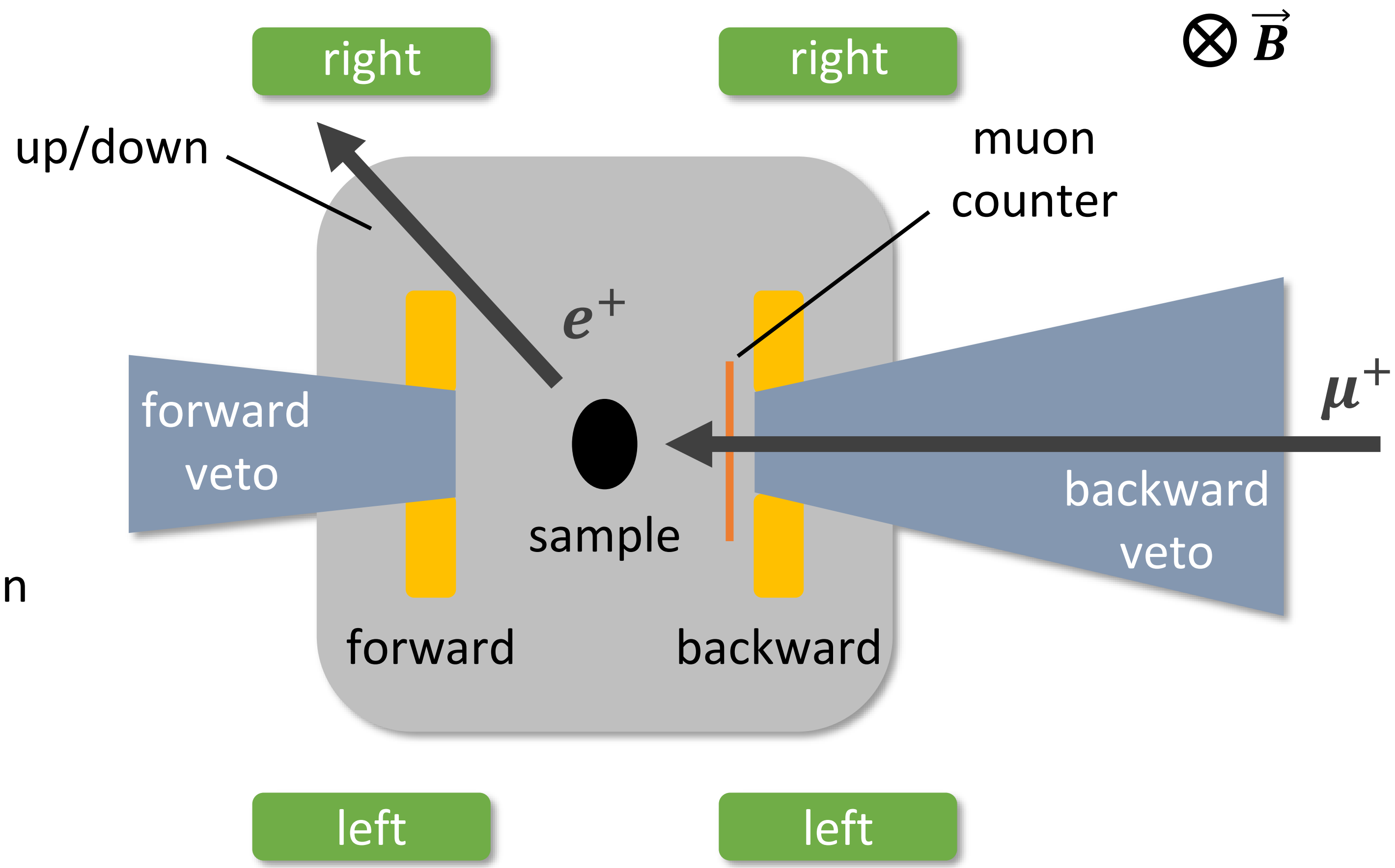
  - Maximal 1 muon per time frame
  - Limited observation time
  - ⇨ 40 kHz (18 kHz acceptance)



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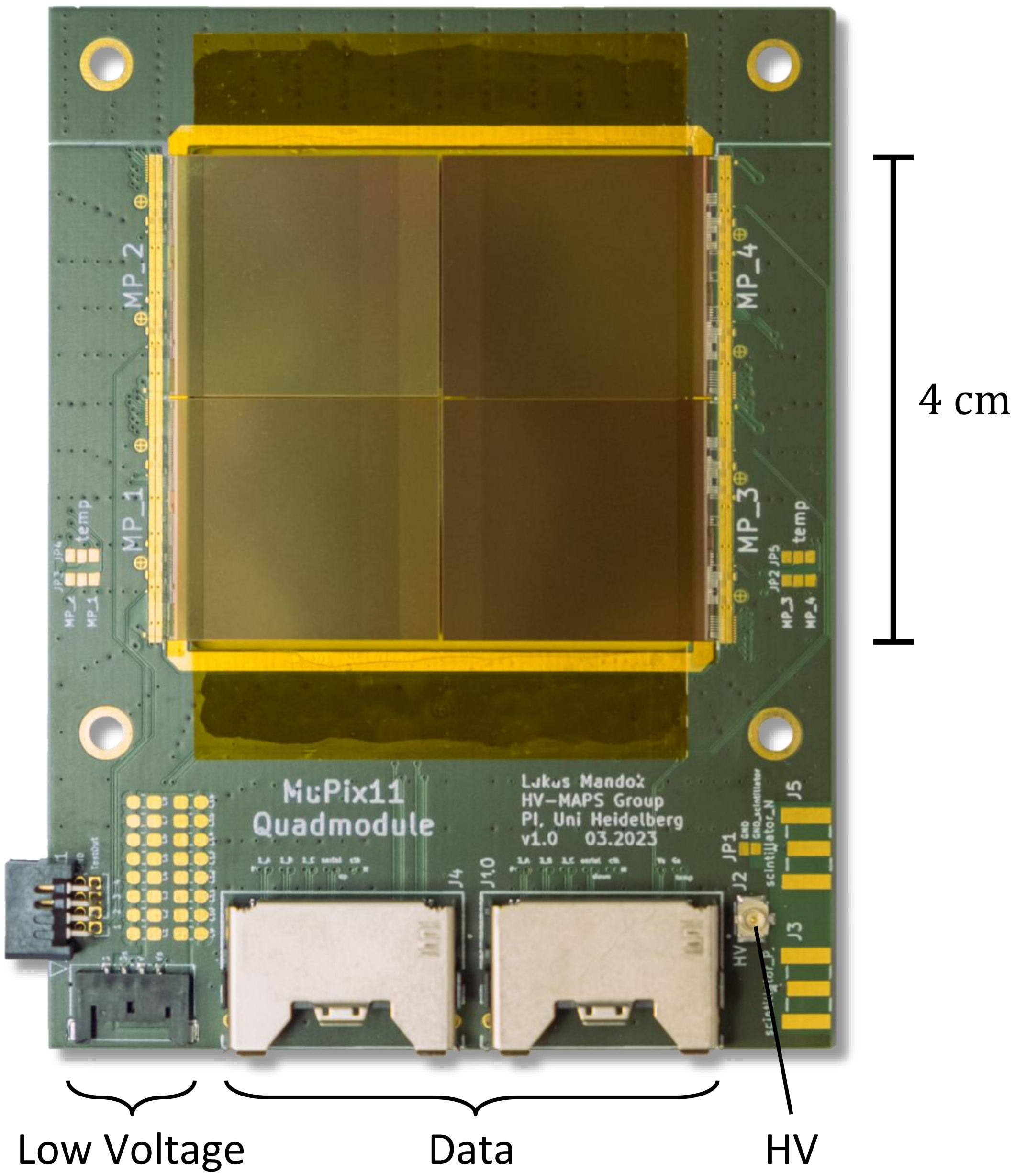
Next Generation

Quad Module

2×2 **MuPix11** Module

- $(4 \times 4)\ \mathrm{cm}^2$ active area
- $50 - 100\ \mu\mathrm{m}$ sensor thickness



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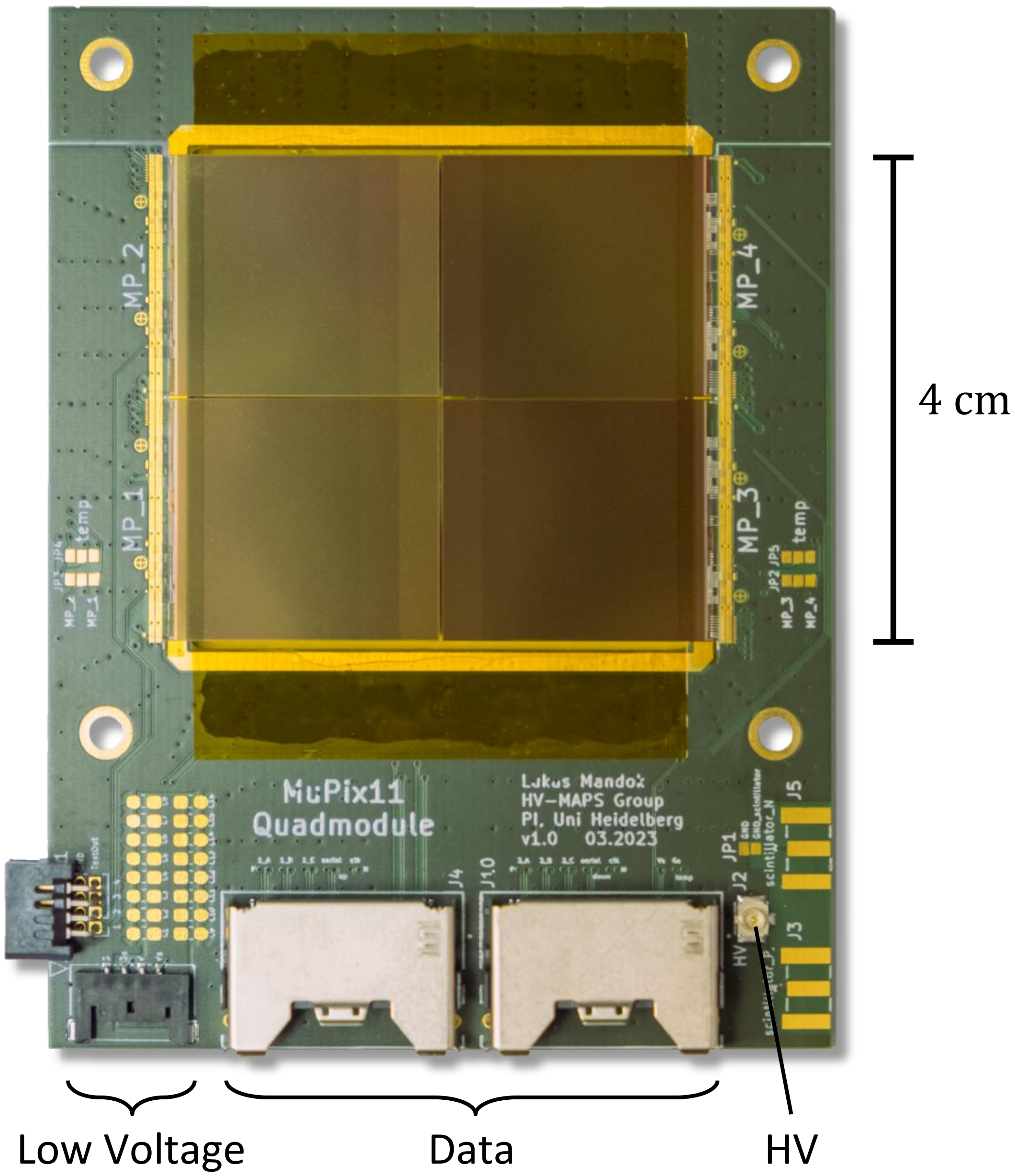
High-Voltage Monolithic Active Pixel Sensor

- 180 nm HV-CMOS technology

MuPix11:		
	Pixel Matrix:	256×250
	Pixel Size:	$(80 \times 80)\ \mu\mathrm{m}^2$
	Time Binning:	8 ns
	Datalink Speed:	3×1.25 Gbps

More Information:
Heiko Augustin
Thomas Rudzki

⇨ Poster Session (Mupix11 Quality Control)



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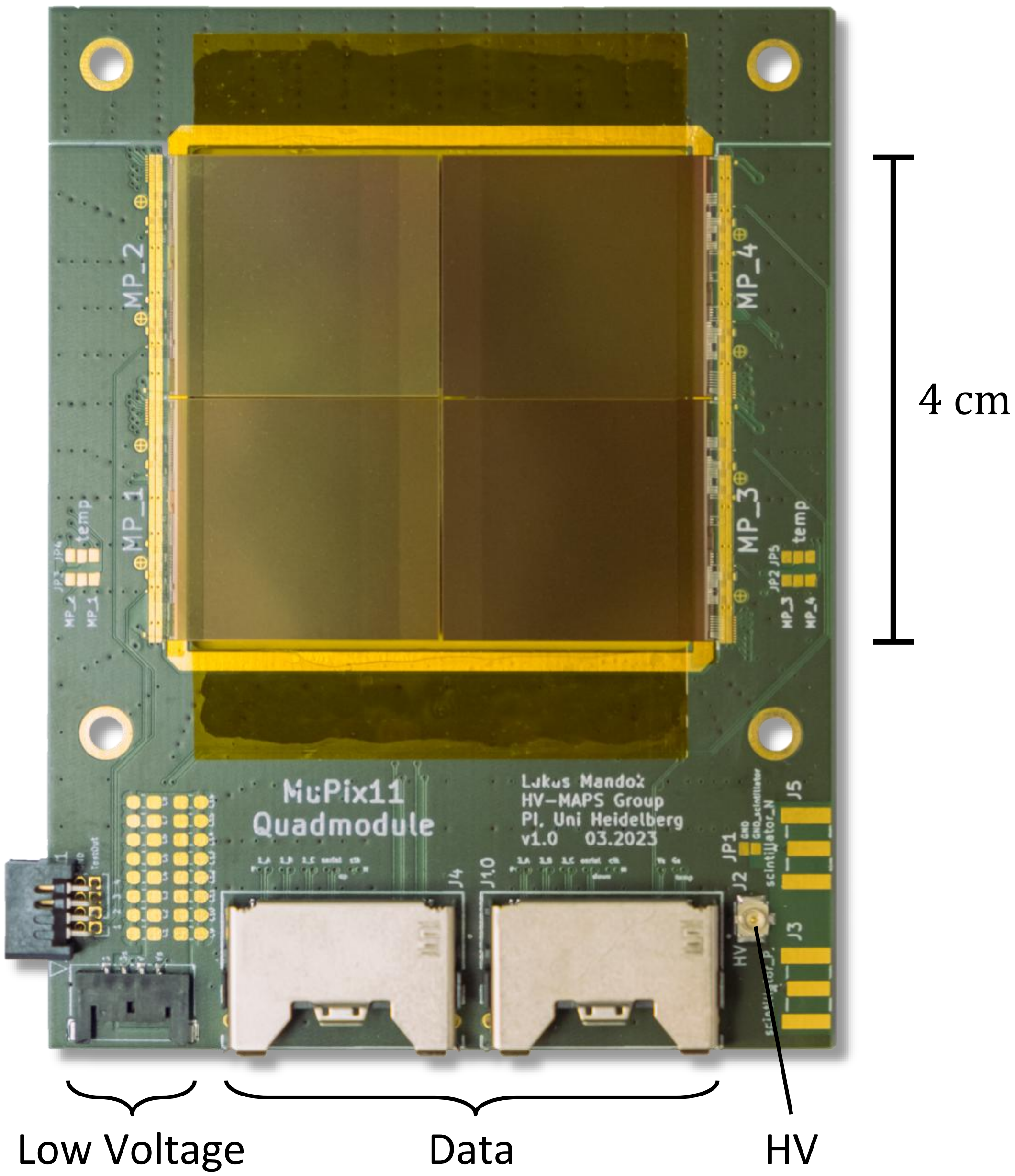
⇨ reduce multiple Coulomb scattering



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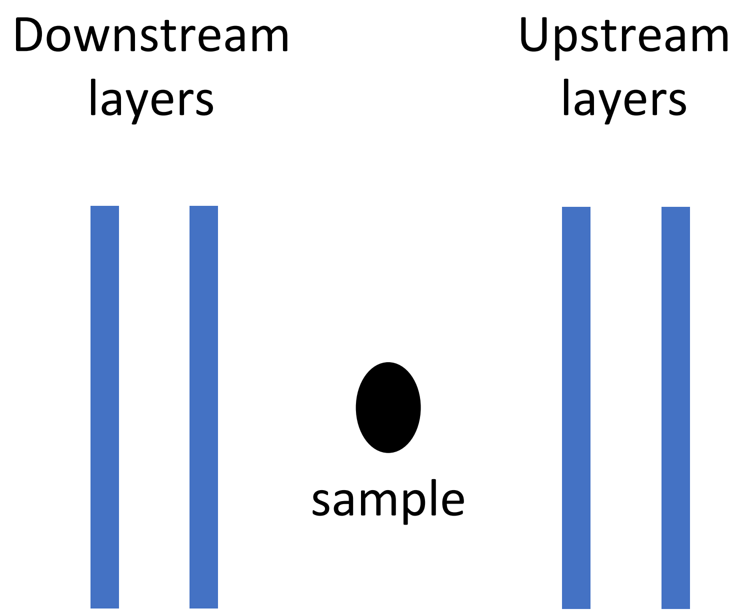
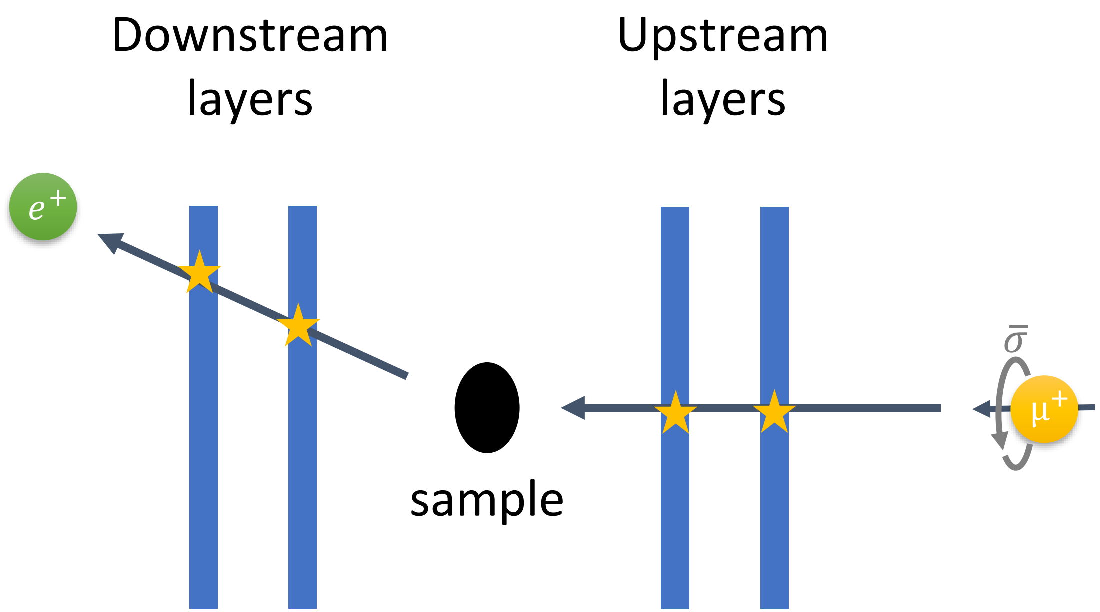


Next Generation
Pixel-based Detector

- 2-layer tracking using pixel sensors



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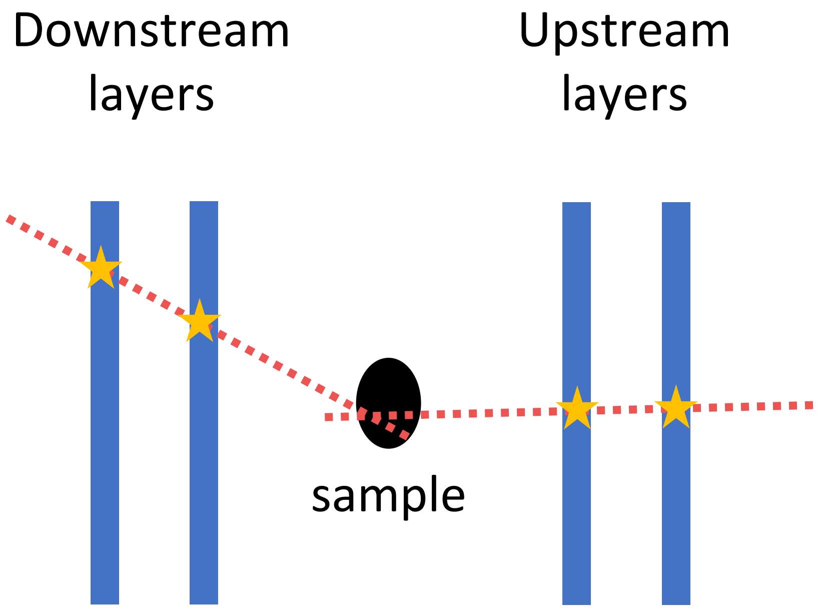
- 2-layer tracking using pixel sensors
  ⇨ Tracklet matching in **Corryvreckan**



Next Generation

Pixel-based Detector

- 2-layer tracking using pixel sensors
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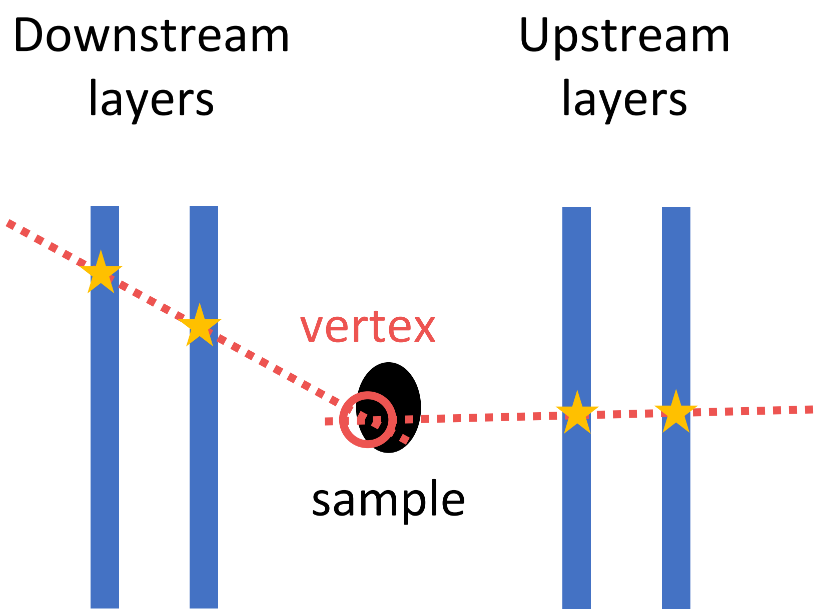
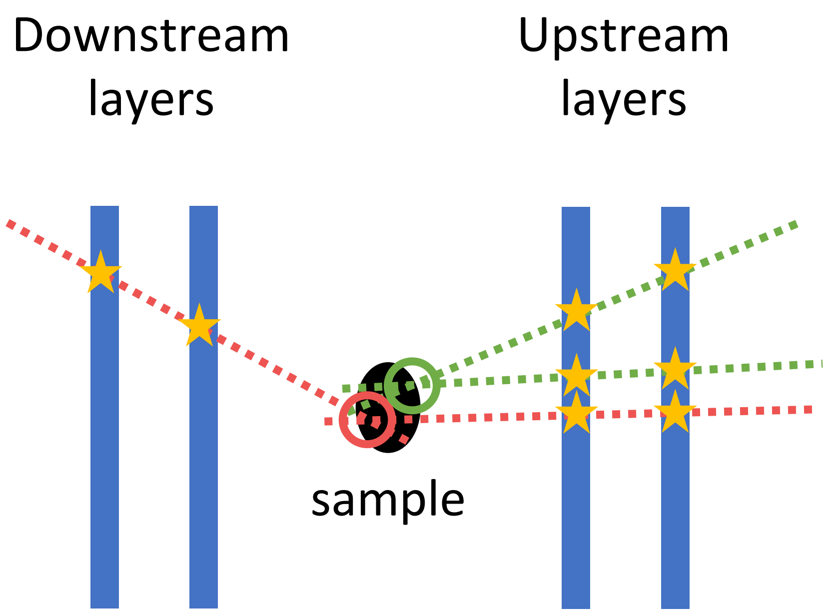
- Basic vertex reconstruction



Next Generation
Pixel-based Detector

- 2-layer tracking using pixel sensors
  - ⇨ Tracklet matching in **Corryvreckan**
- Basic vertex reconstruction
  - ⇨ Differentiate between simultaneous events



Next Generation
Pixel-based Detector

- 2-layer tracking using pixel sensors
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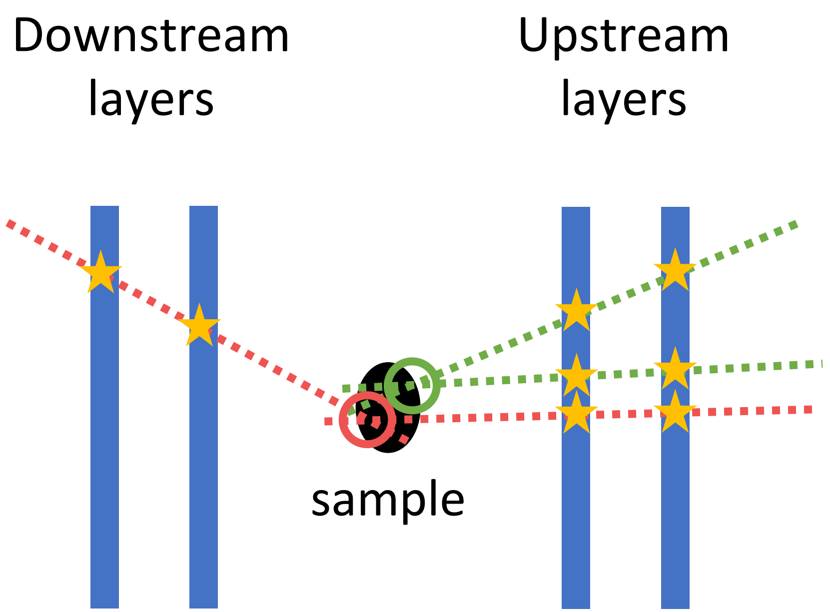
- Theoretical improvements:
  ⇨ Increase muon rate by 10 – 100 times
  ⇨ Increase observation time
  ⇨ Several smaller samples at once
  ⇨ Probe local domains within sample



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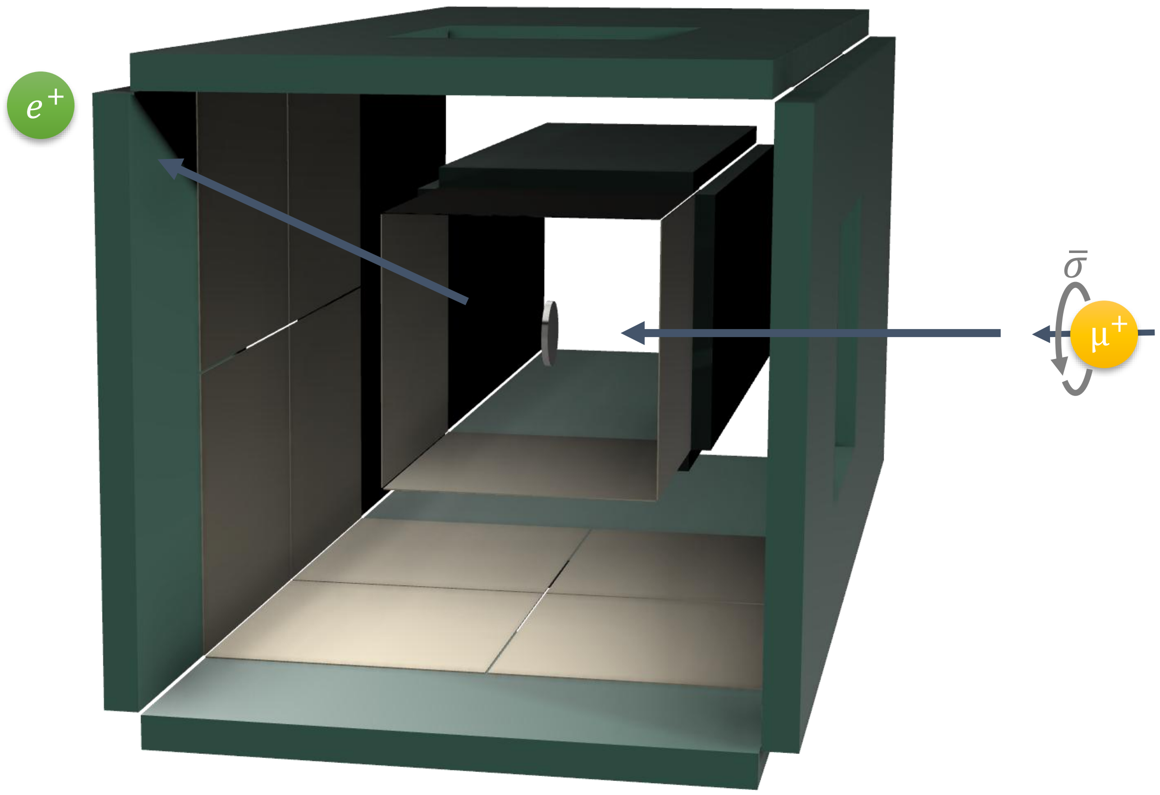
Conceptual full-scale detector



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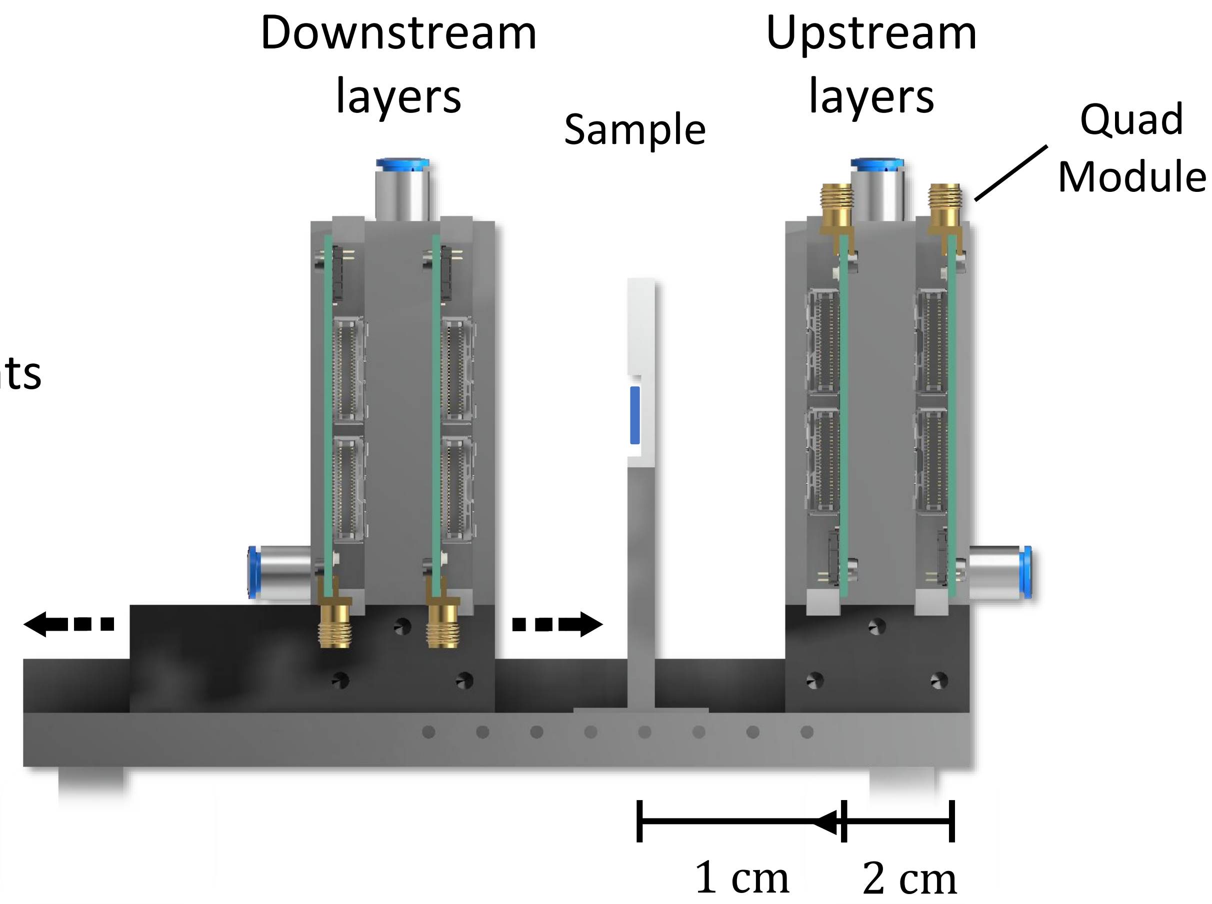
Prototype detector



μSR Setup

Testbeam Telescope

- Transversal polarized surface μ^+ beam @ PSI – PiE3 beamline (HAL 9500)

μSR Setup
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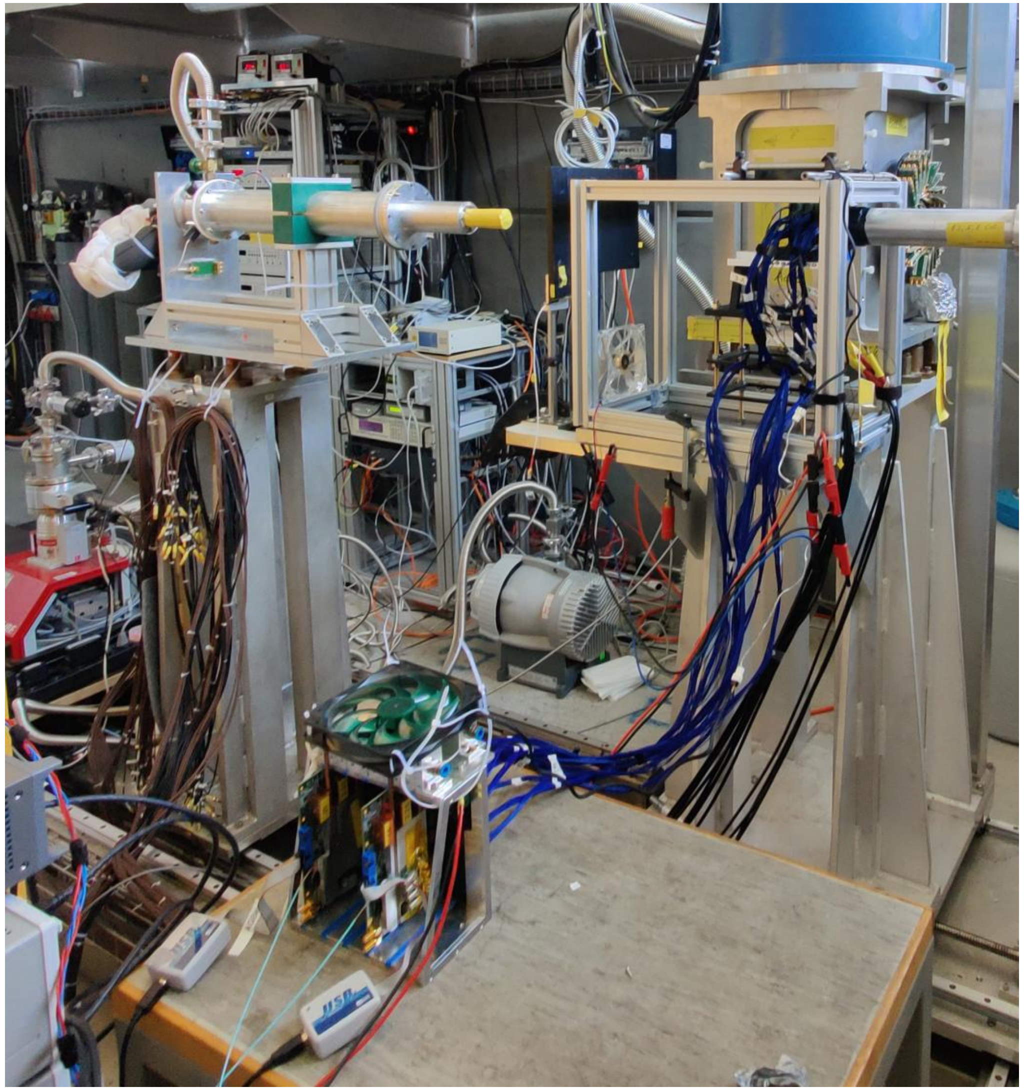
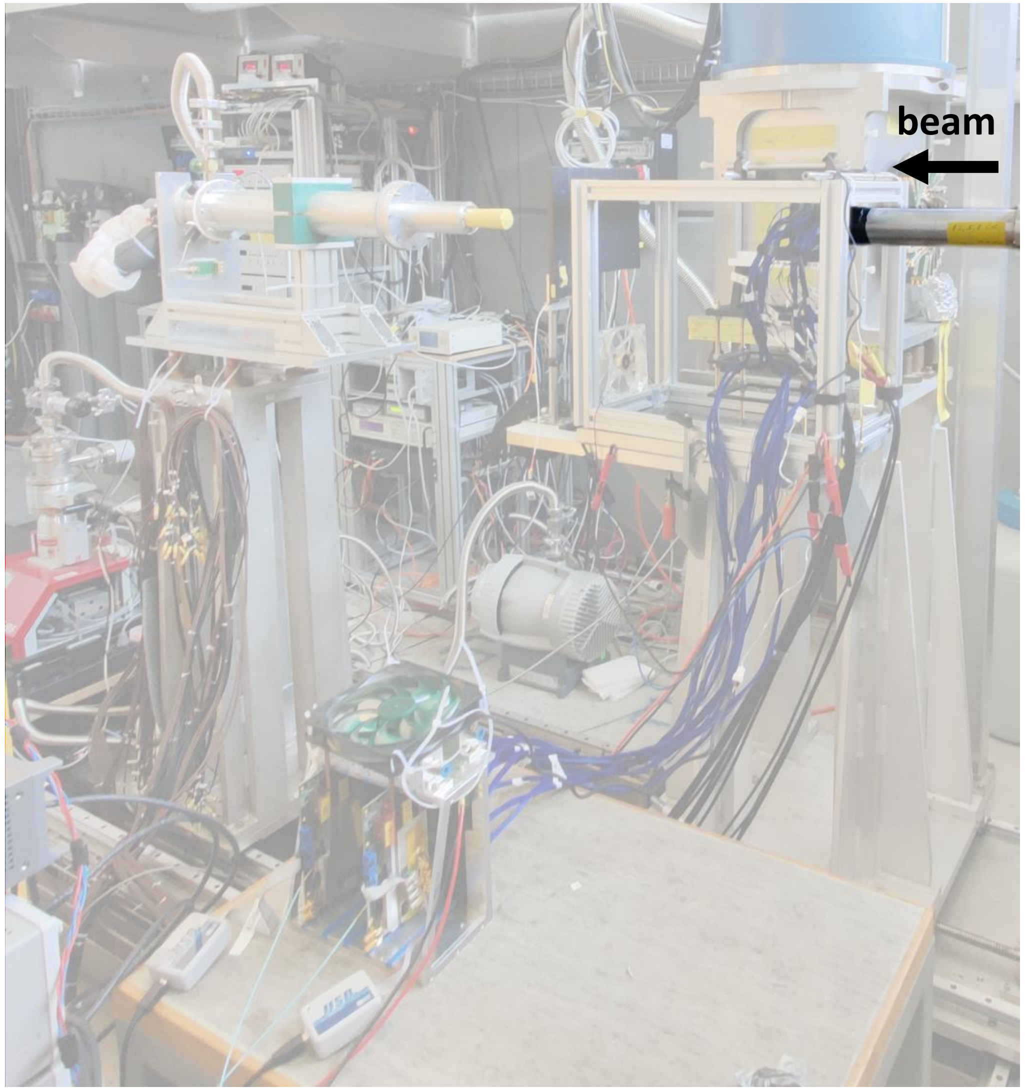
- Goals
  - Measuring vertex resolution $< 1\ \mathrm{mm}$
  - Measuring spin rotation
  - Mapping magnetic field in sample

  - General setup characterization
  - Measuring forward backward asymmetry
  - Multiple sample / High-rate capability
  - PID using charge deposition

µSR Setup
DAQ

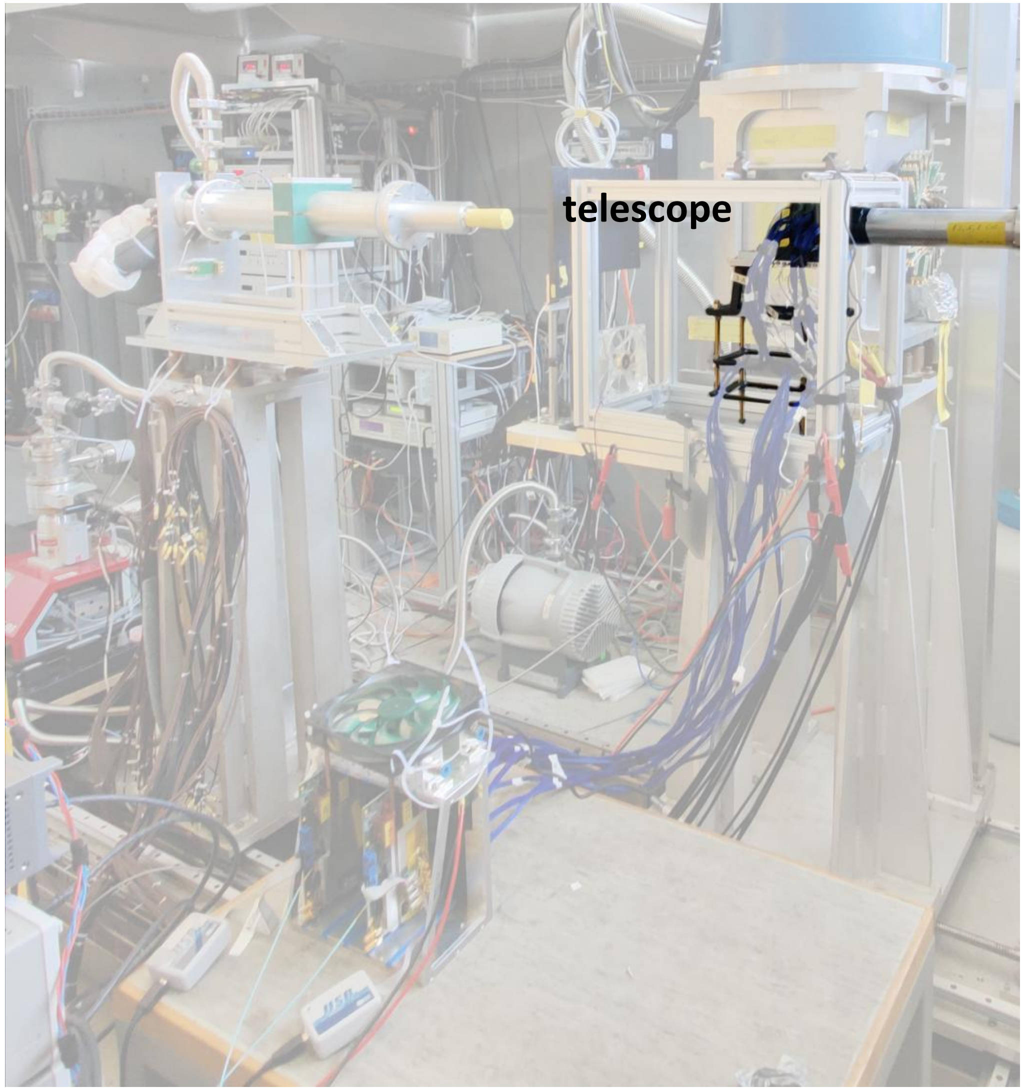


μSR Setup
DAQ



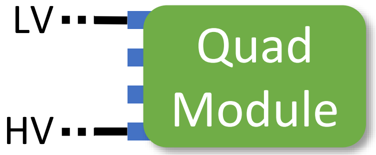
µSR Setup
DAQ

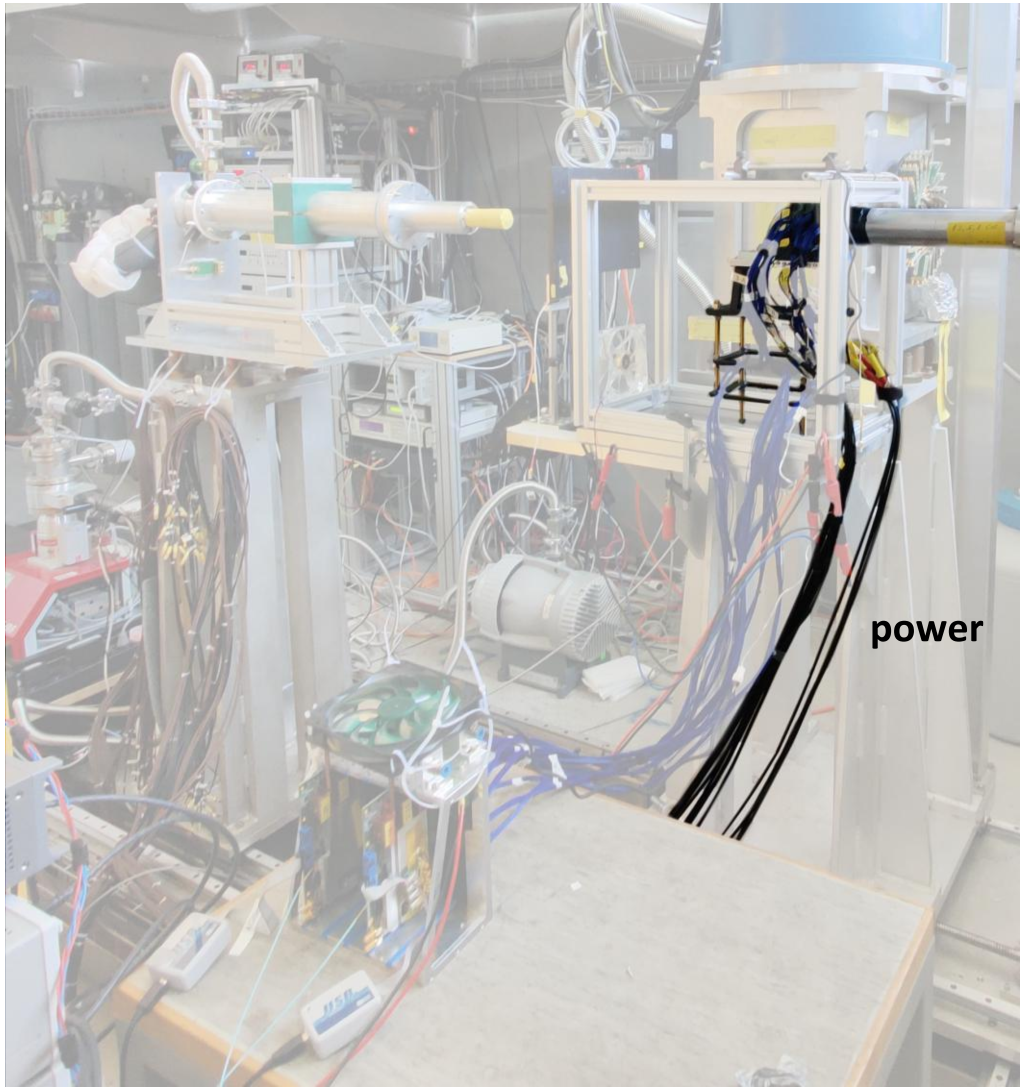
Quad
Module



µSR Setup

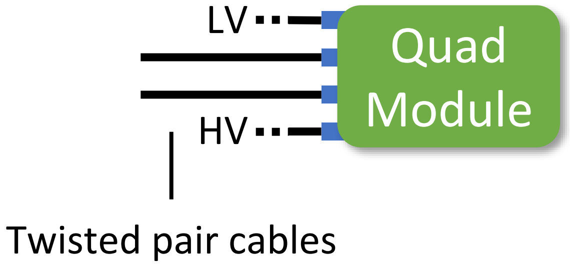
DAQ

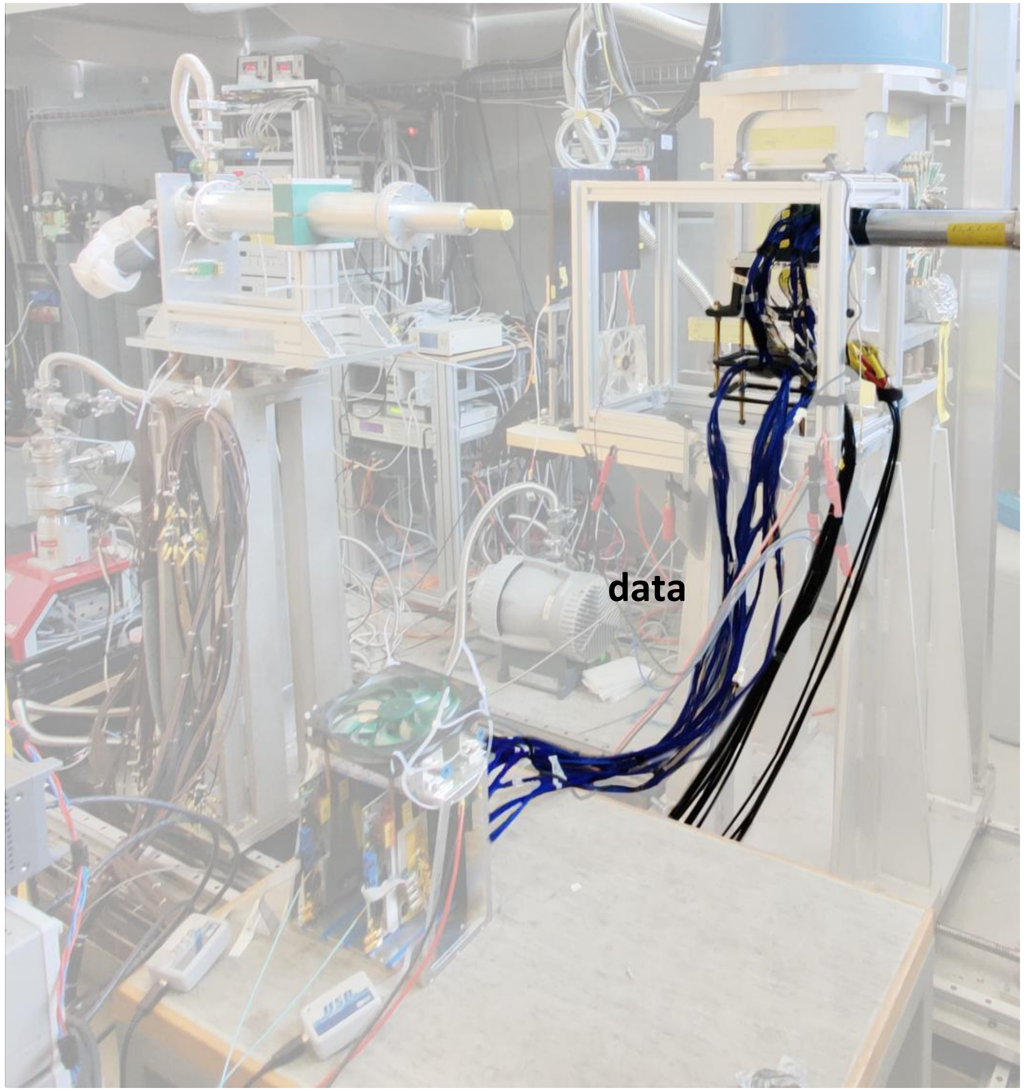




μSR Setup
DAQ

- 3 data-links per sensor $\times$ 1.25 Gbps





µSR Setup

DAQ

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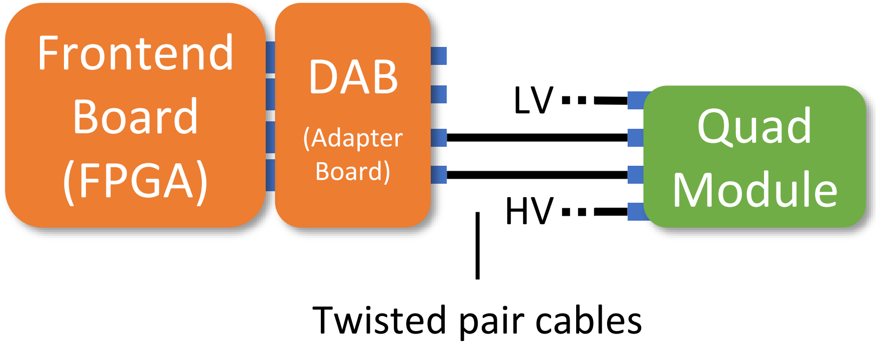
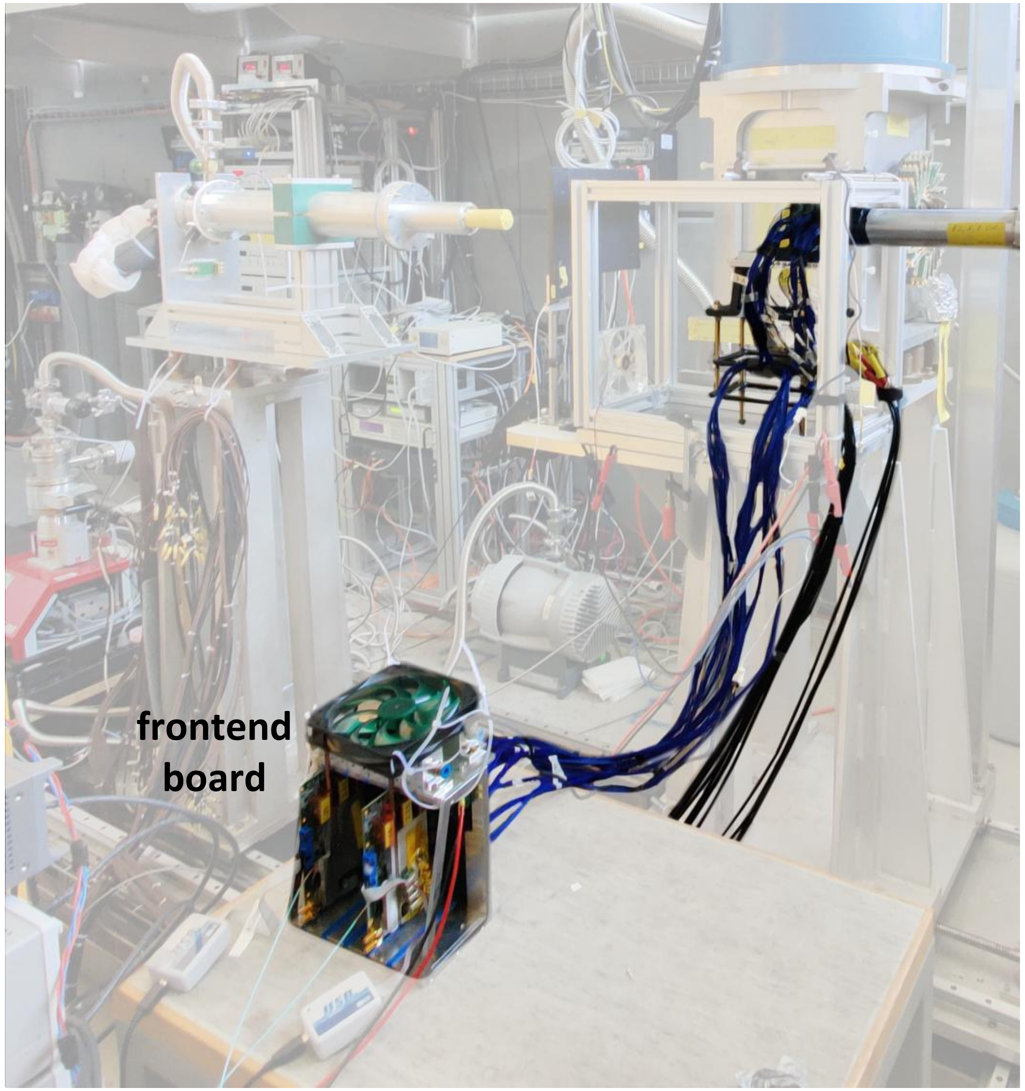
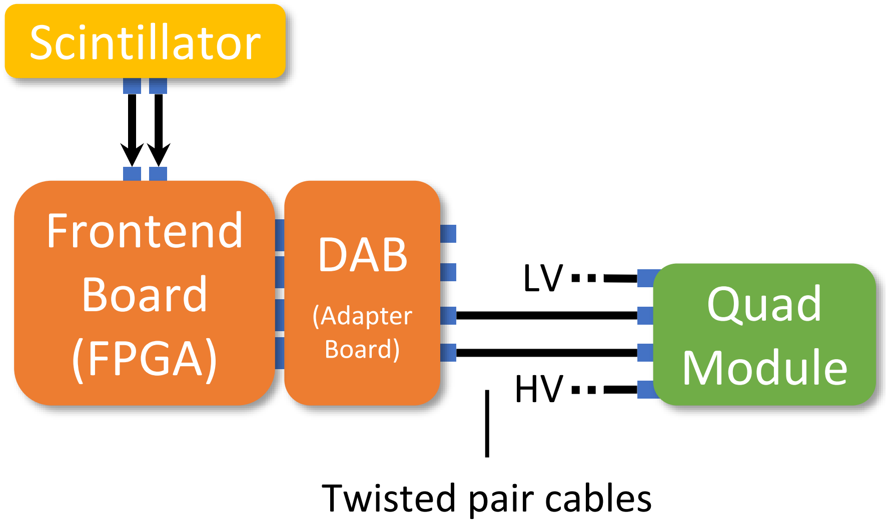
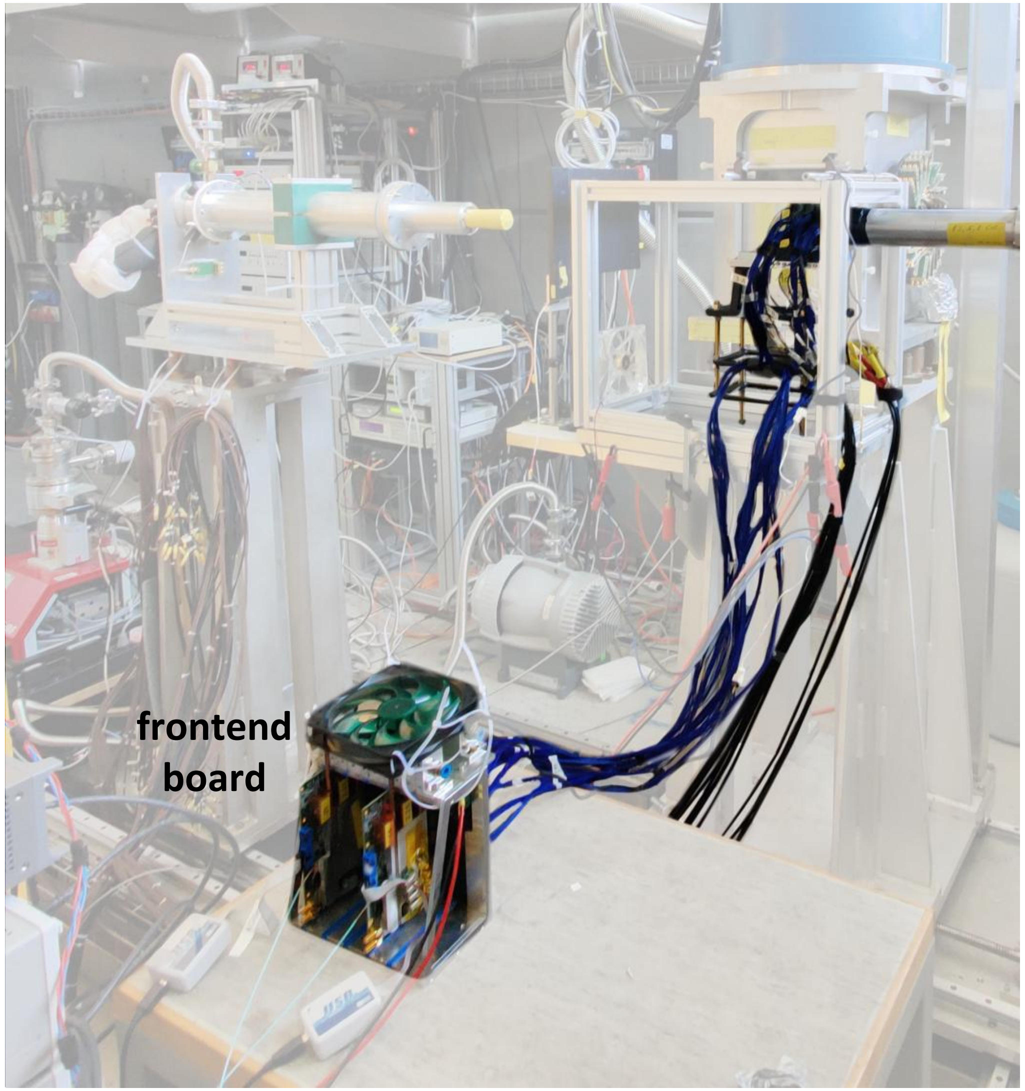




µSR Setup
DAQ

- 3 data-links per sensor × 1.25 Gbps





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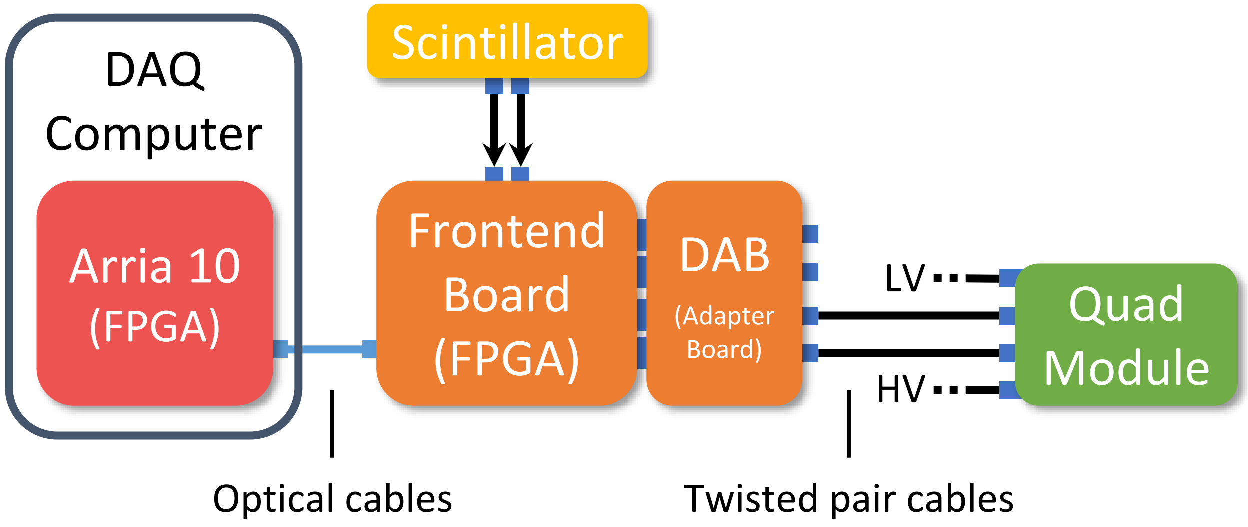
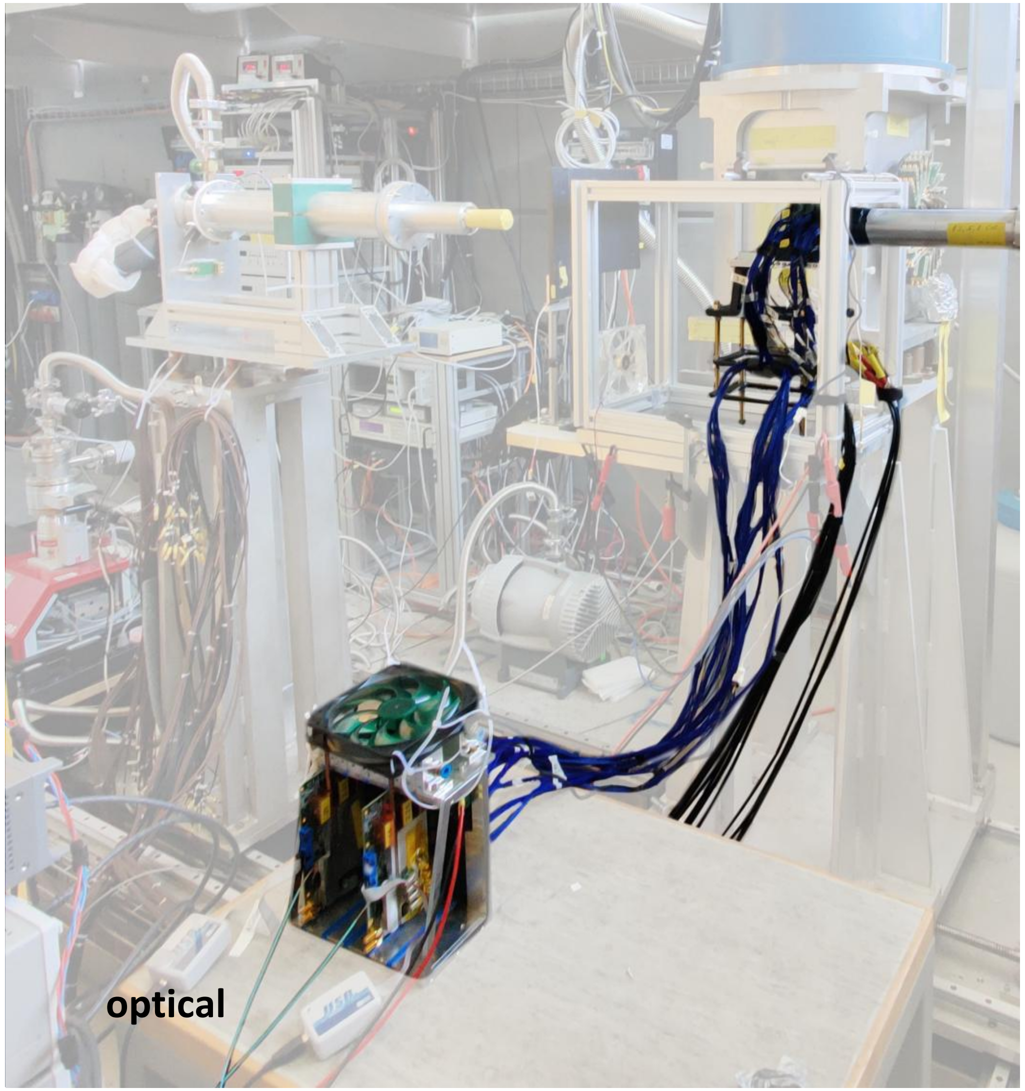
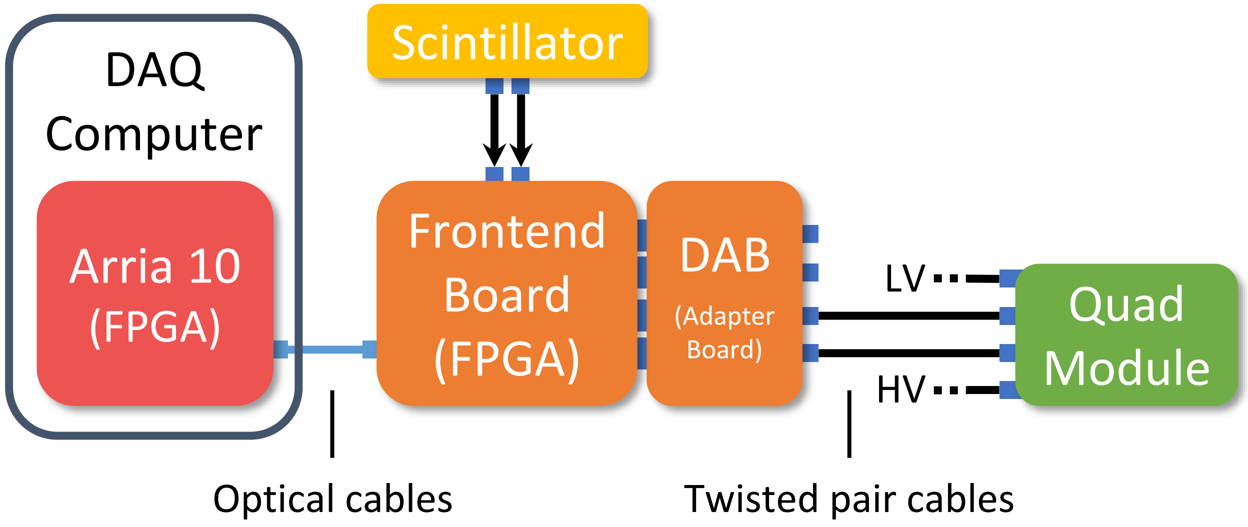
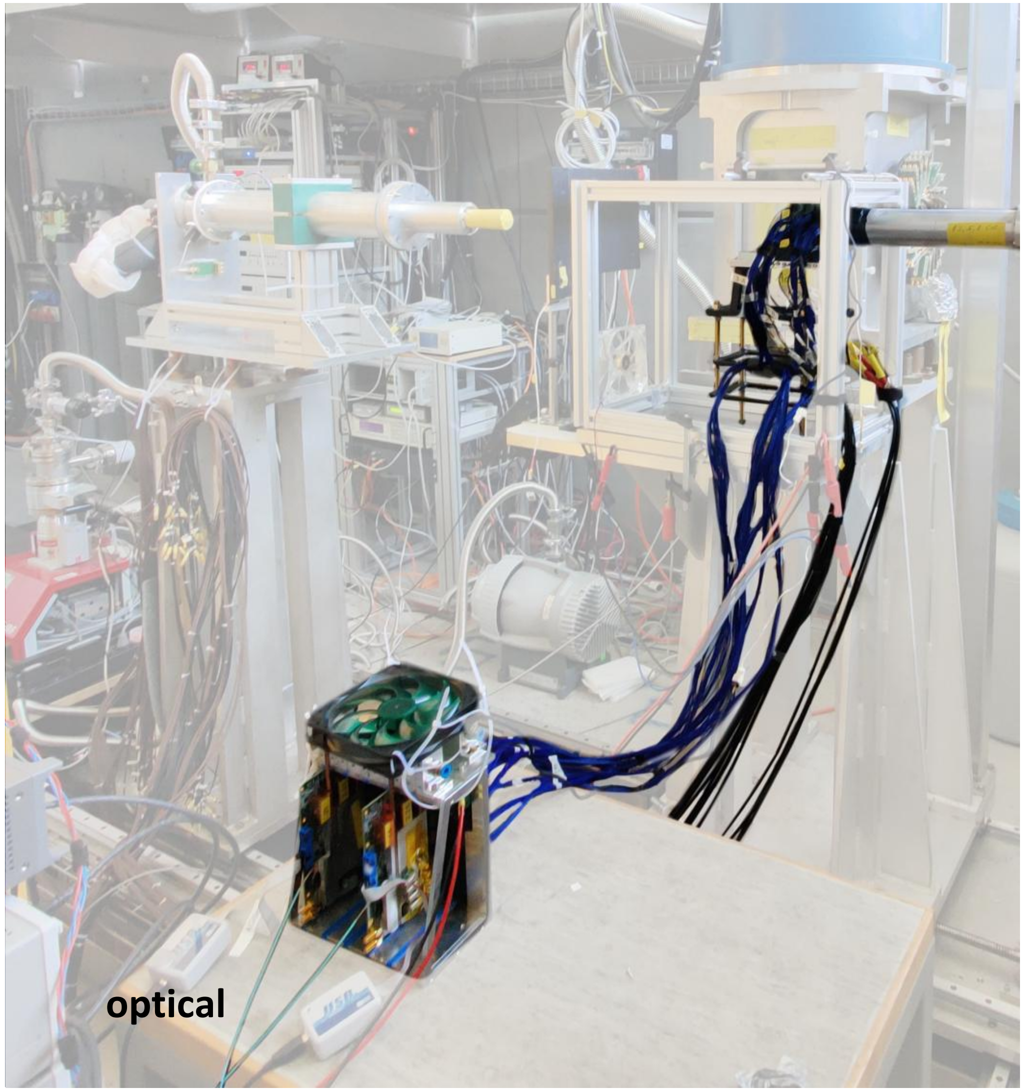




µSR Setup
DAQ

- 3 data-links per sensor $\times$ 1.25 Gbps
- Mu3e soft- and hardware





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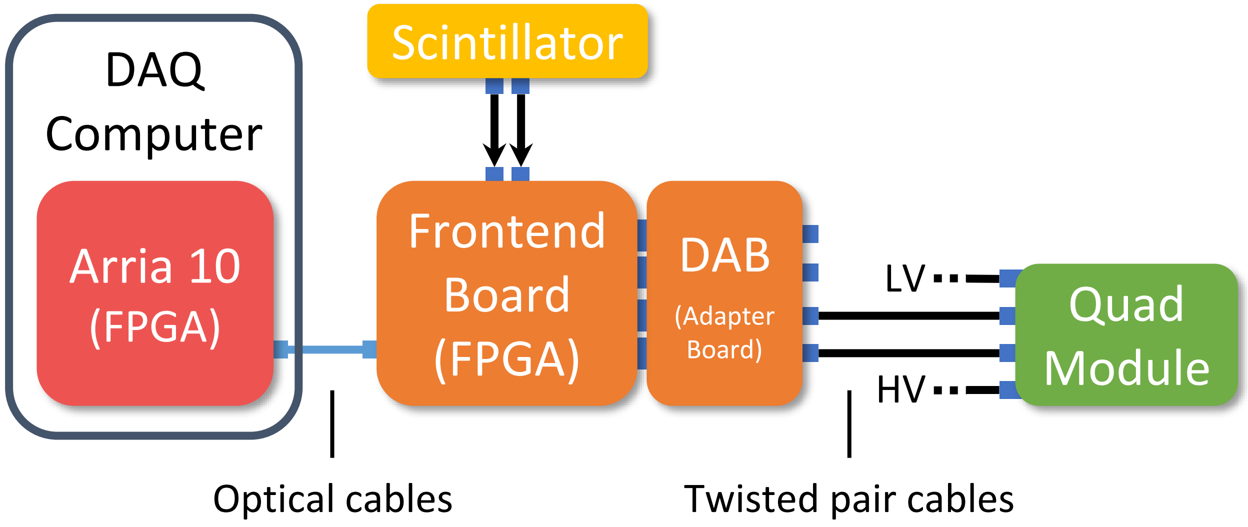

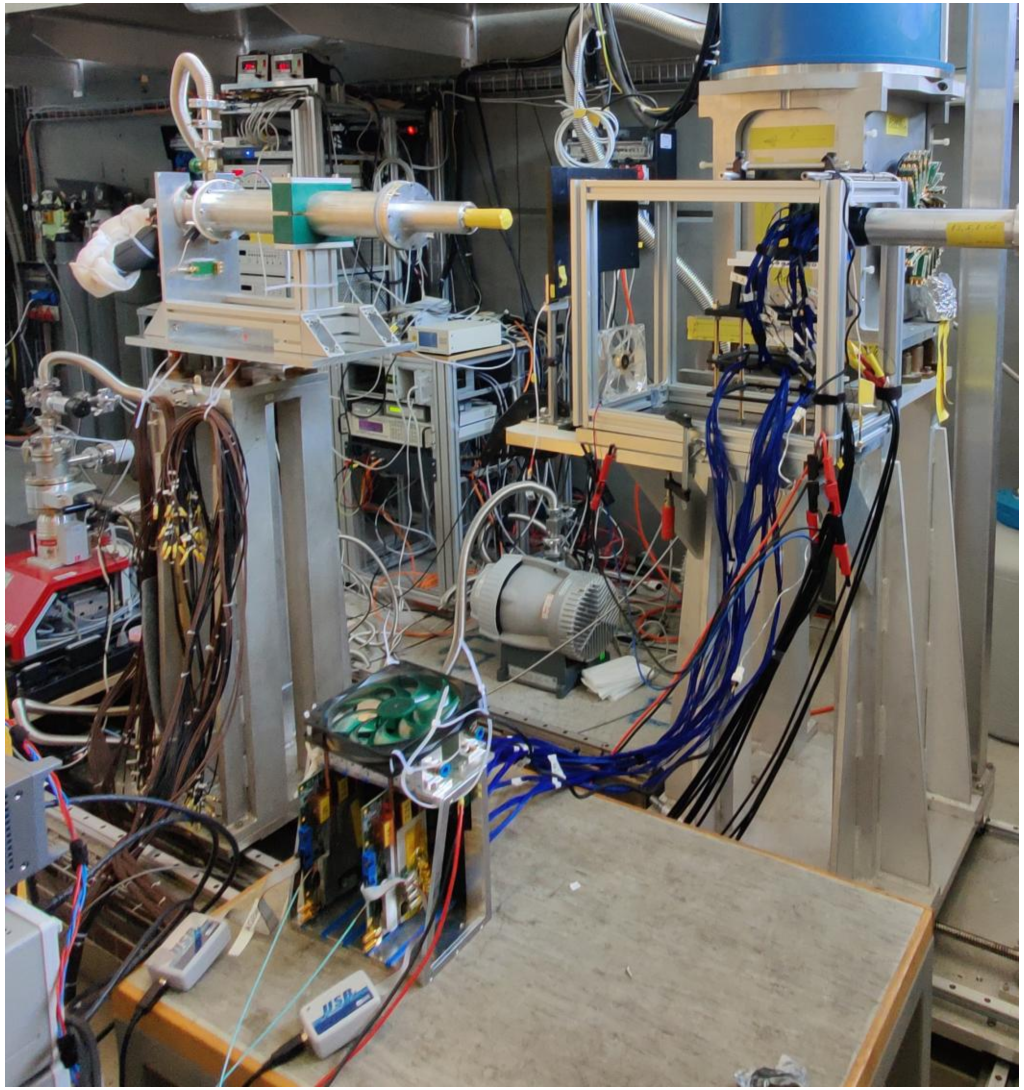

µSR Setup

DAQ

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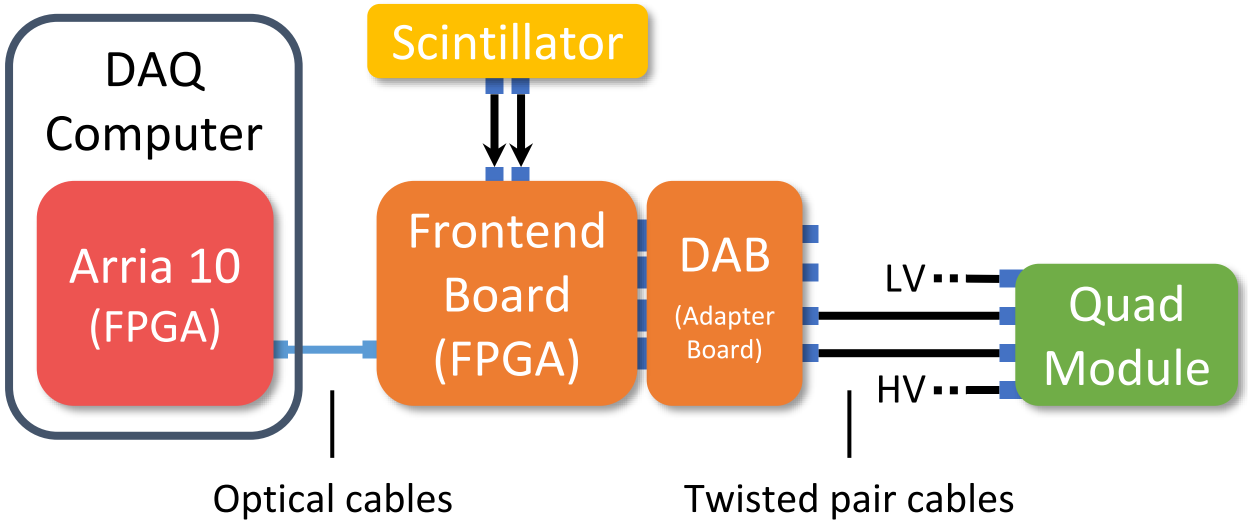
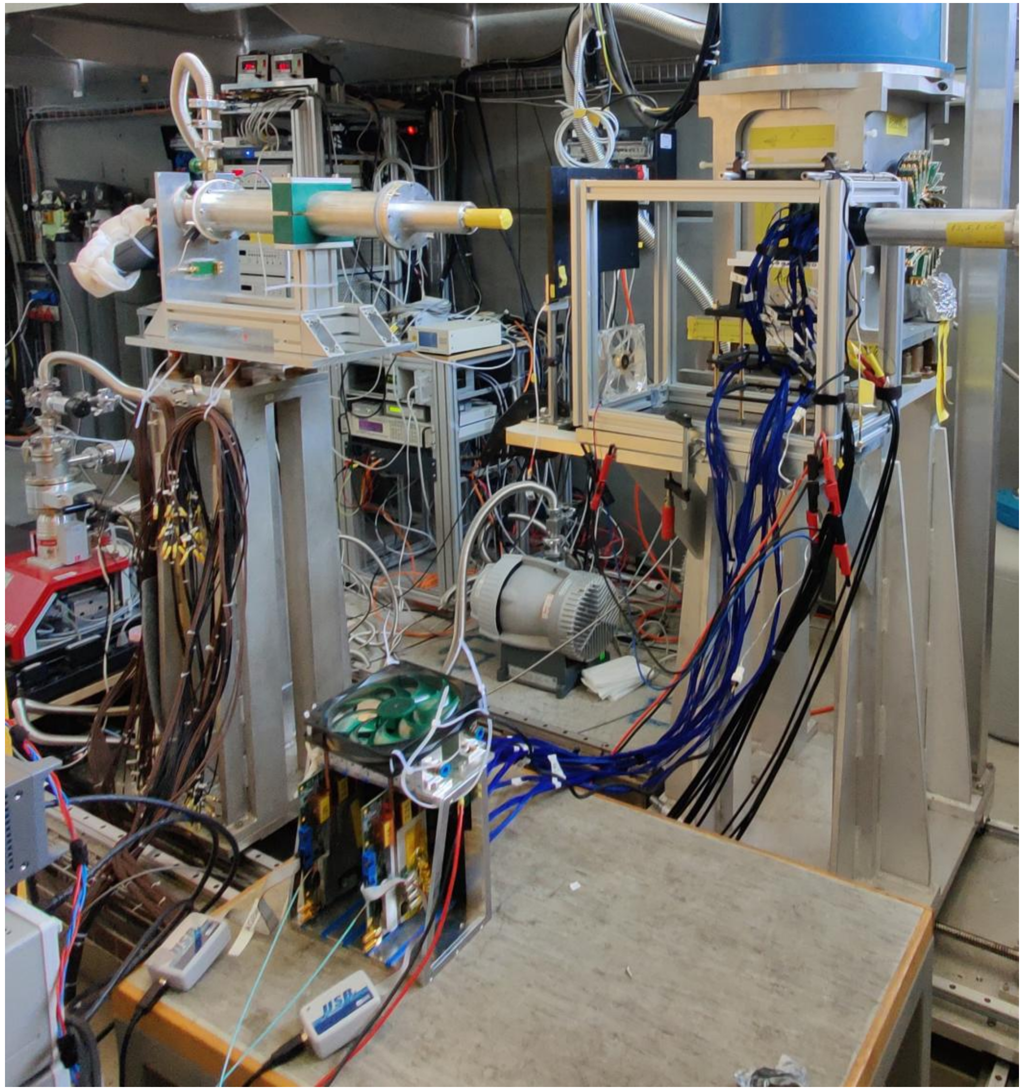
- Mu3e soft- and hardware
- Light sensitive sensors





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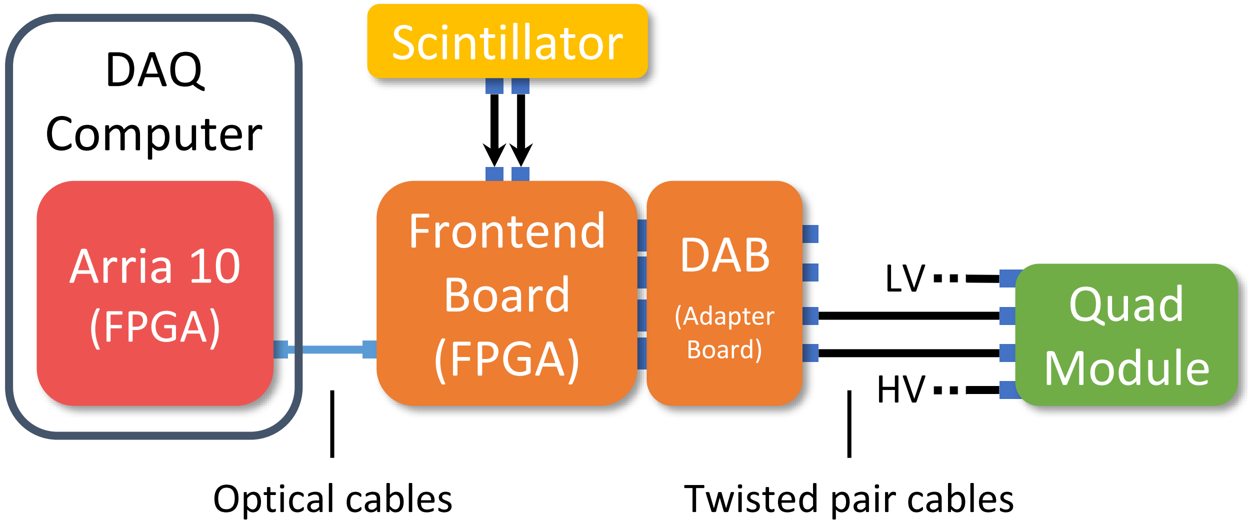
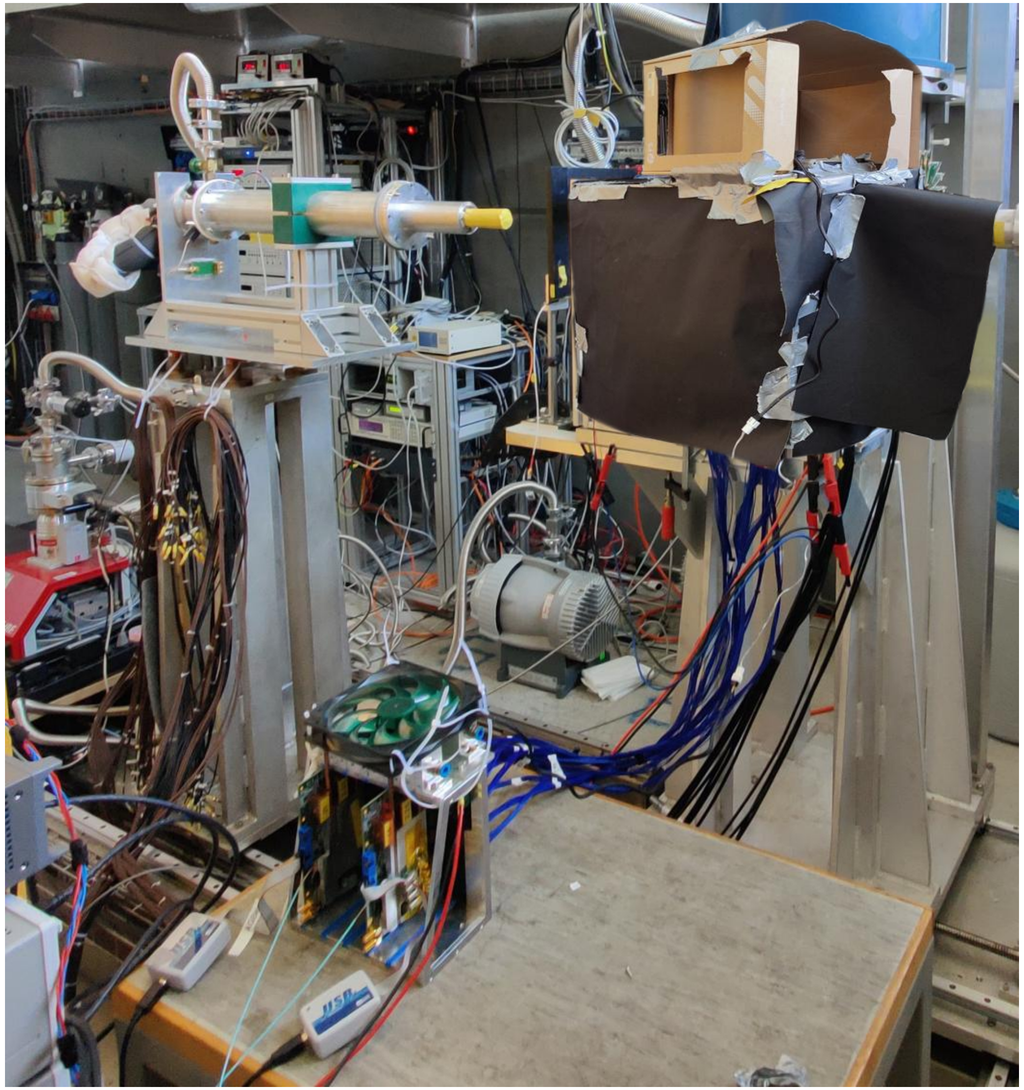
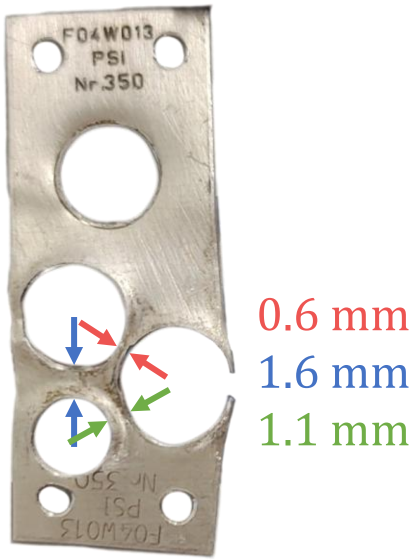




Results

Vertex Resolution

- Sample
  - Improvised silverplate with various cutouts



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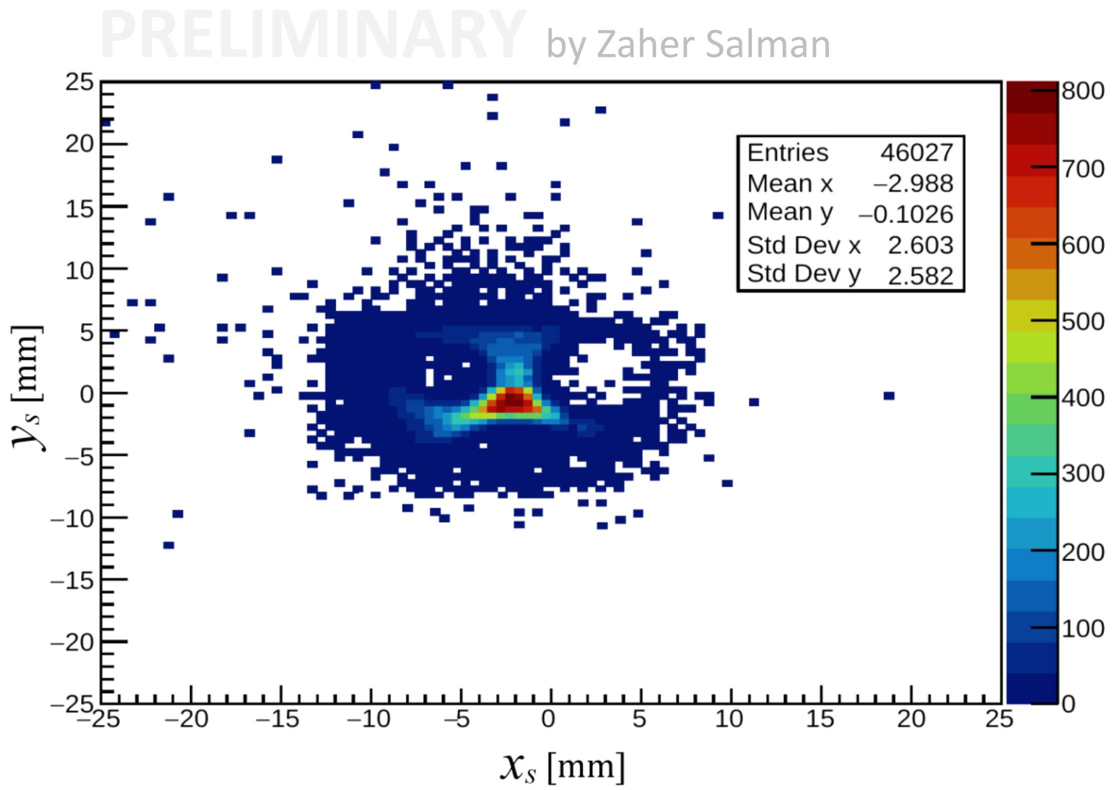

- Sample
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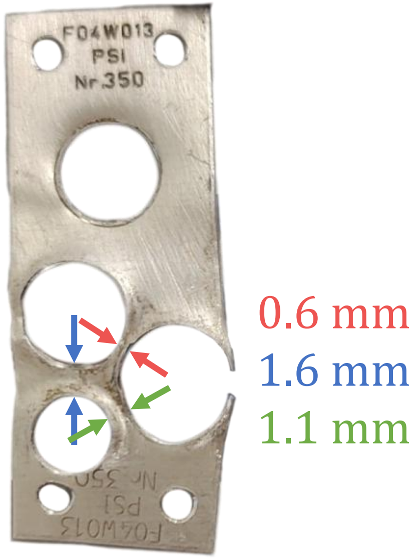
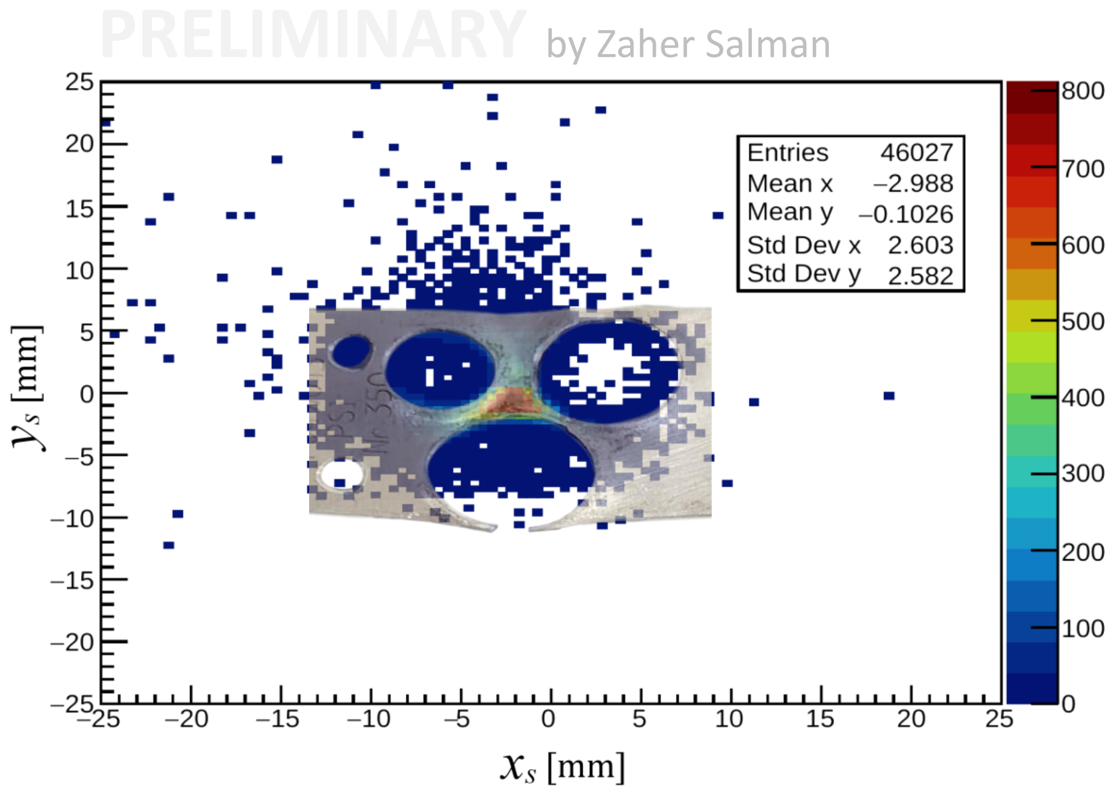


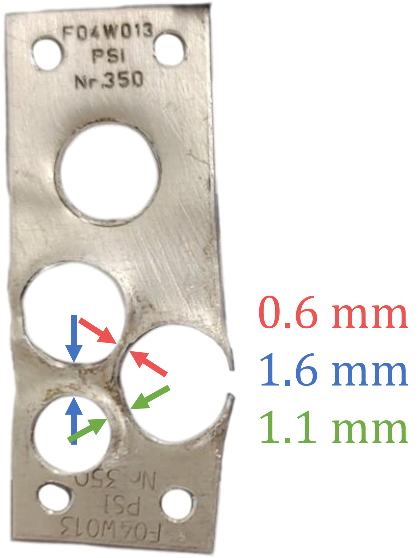
- Results
  - Intersection points of incoming muons and positron trajectories

Results

Vertex Resolution



- **Sample**
  - Improvised silverplate with various cutouts

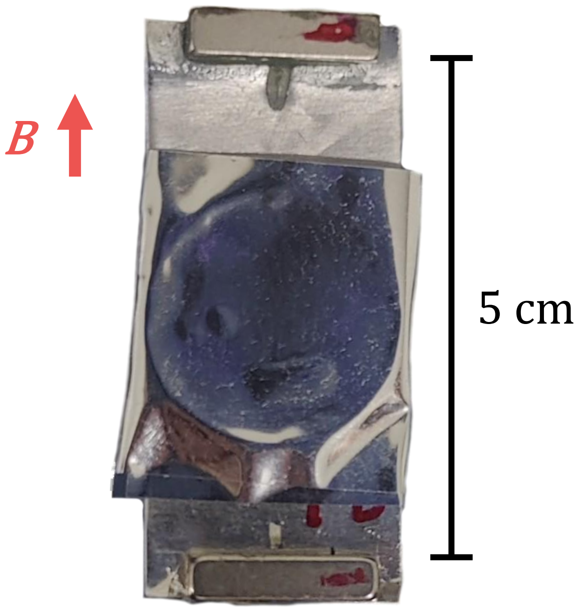


- **Results**
  - Intersection points of incoming muons and positron trajectories
  - Lateral vertex resolution $\leq$ 1 mm

Results

Spin Rotation

- Sample
  - Aluminum disk
  - $\varnothing = 6\ \mathrm{mm}$
  - $B_{\perp} = 6.3\ \mathrm{mT}$



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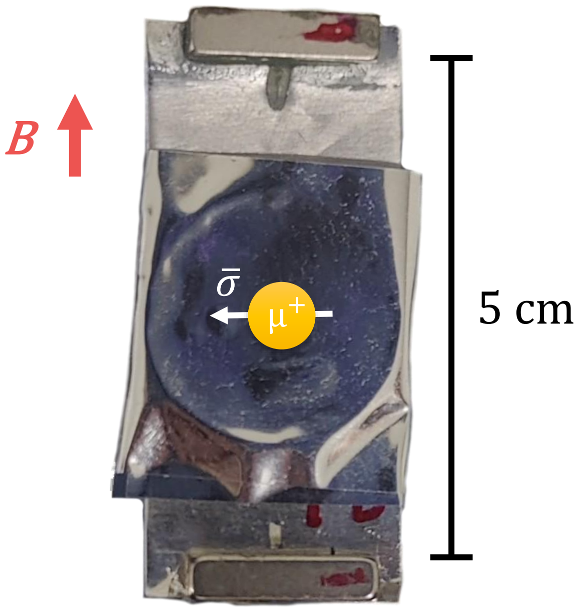

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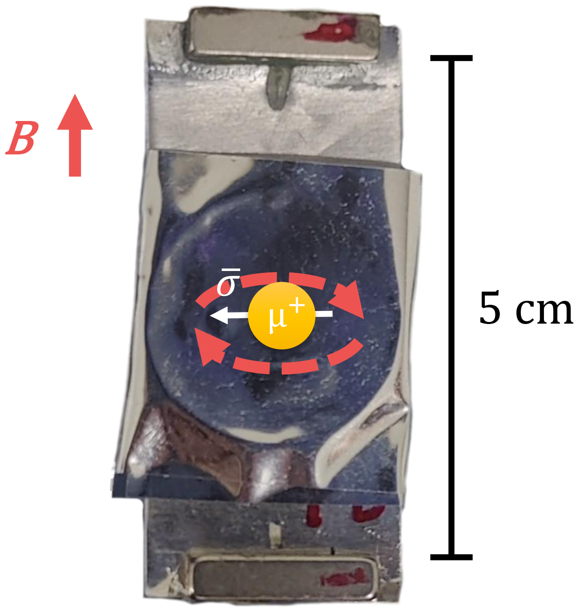

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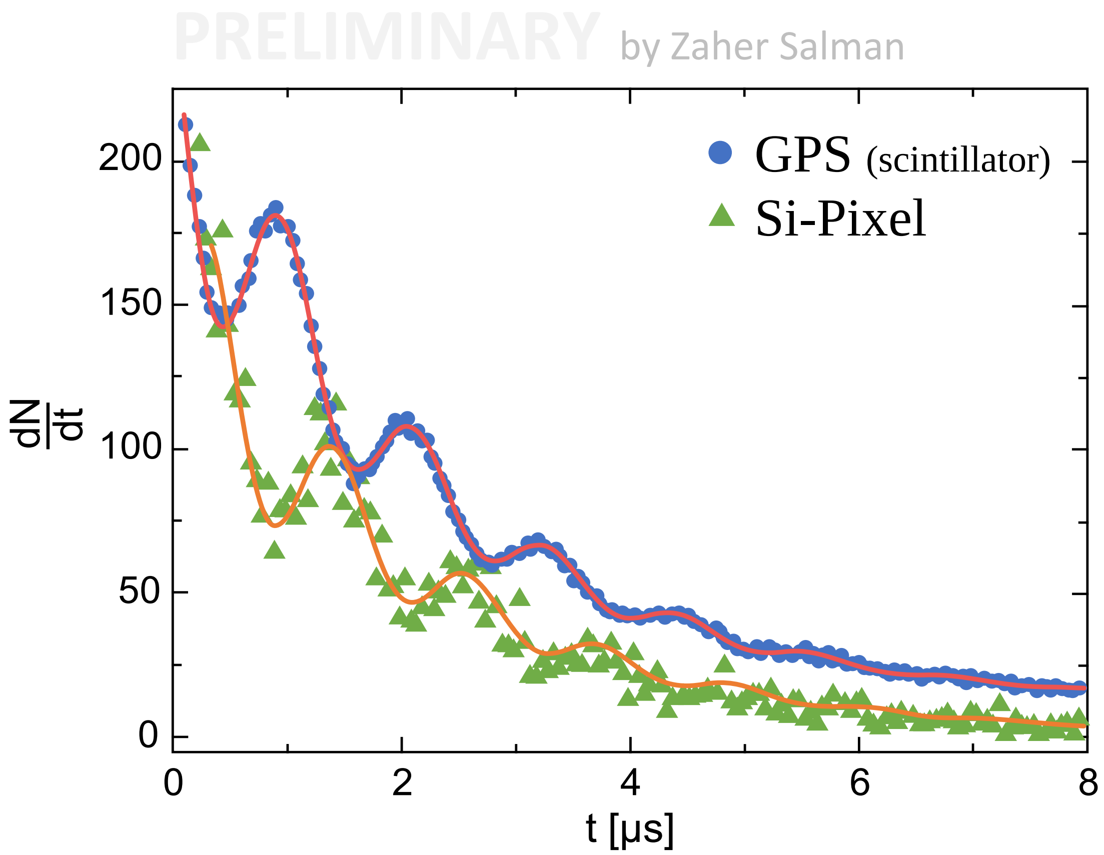

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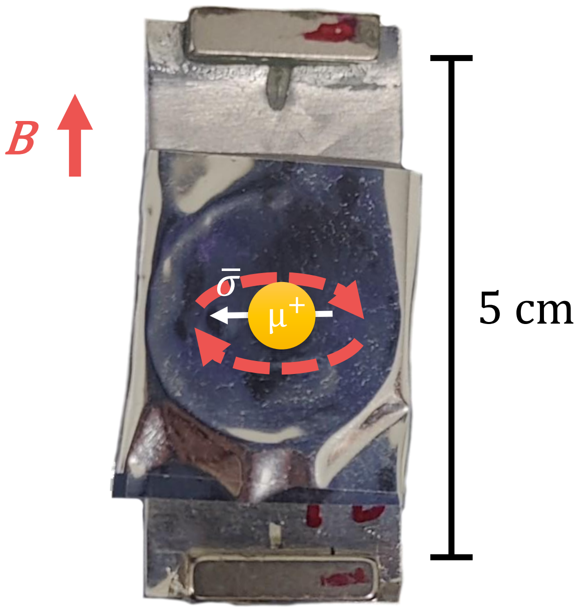

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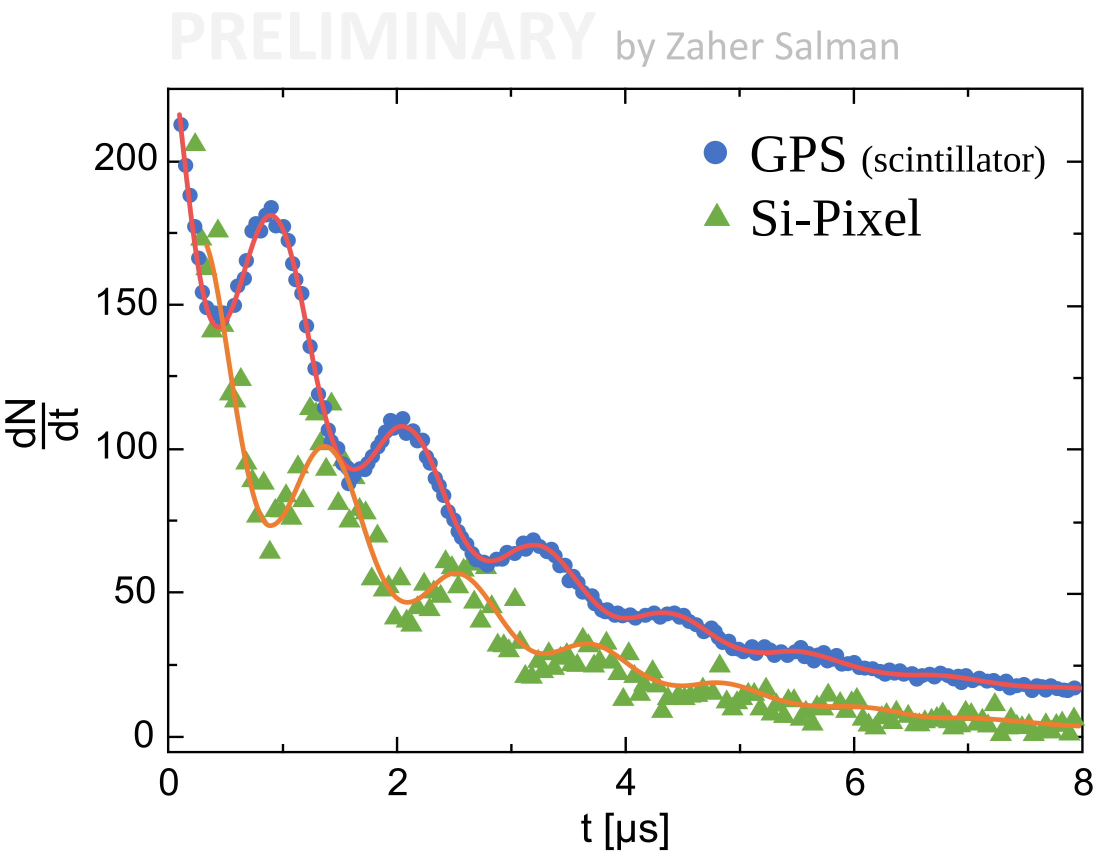

- Sample
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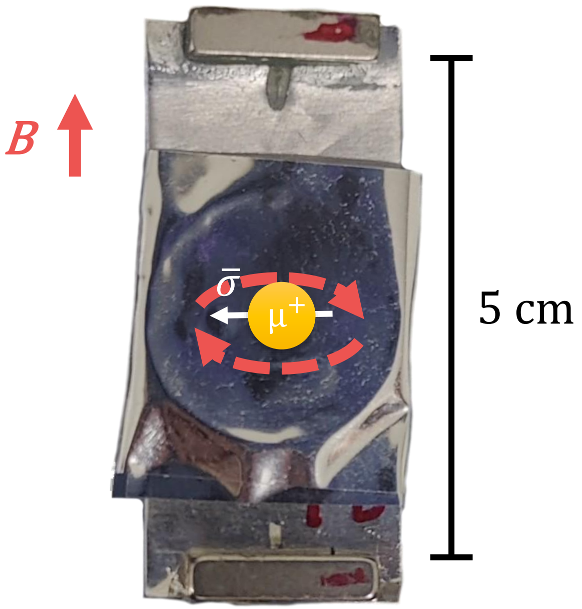
  - $B_{\perp} = 6.3\ \mathrm{mT}$
- Results
  - Low statistics (3 s)
    ⇨ large spread



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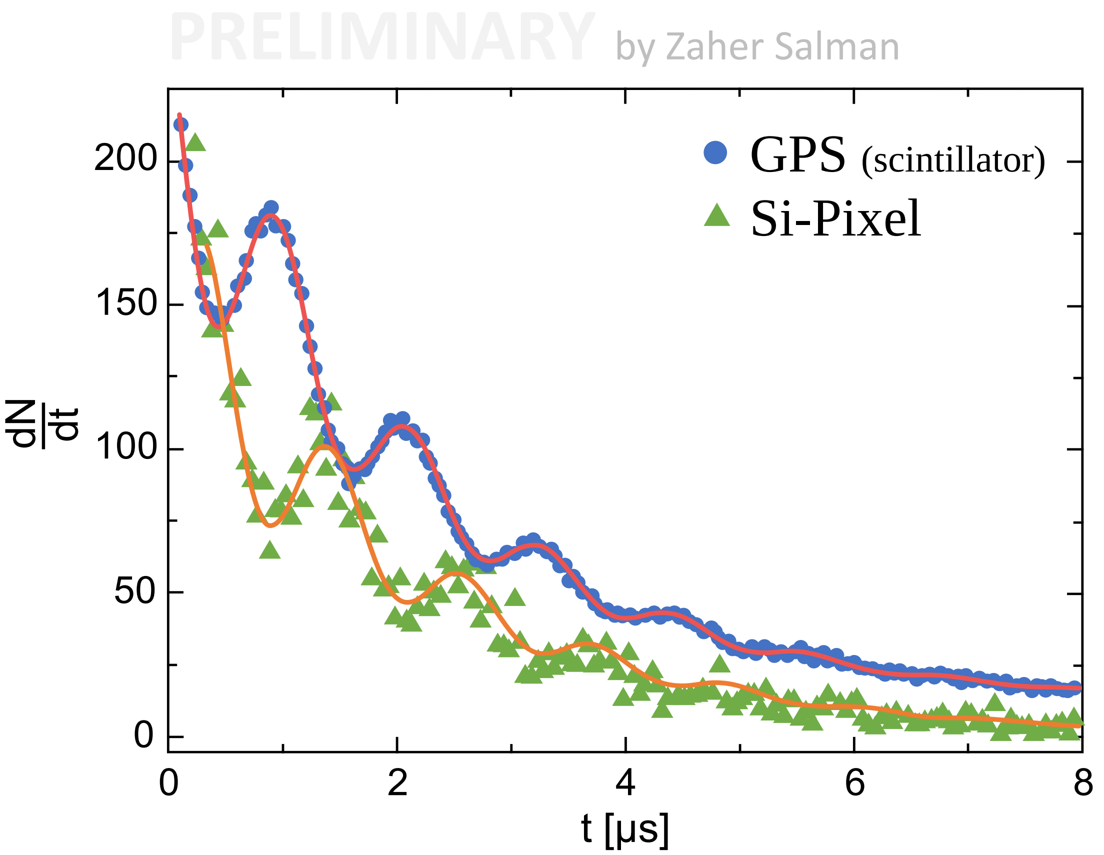
Spin Rotation



- **Sample**
  - Aluminum disk
  - $\emptyset = 6$ mm
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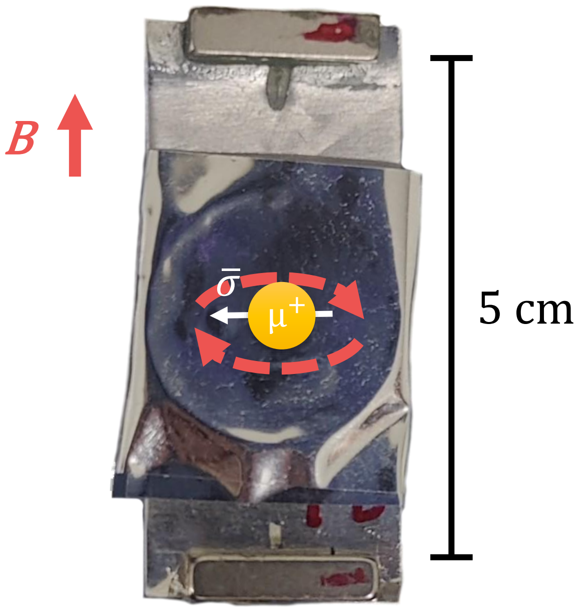

- **Results**
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Results

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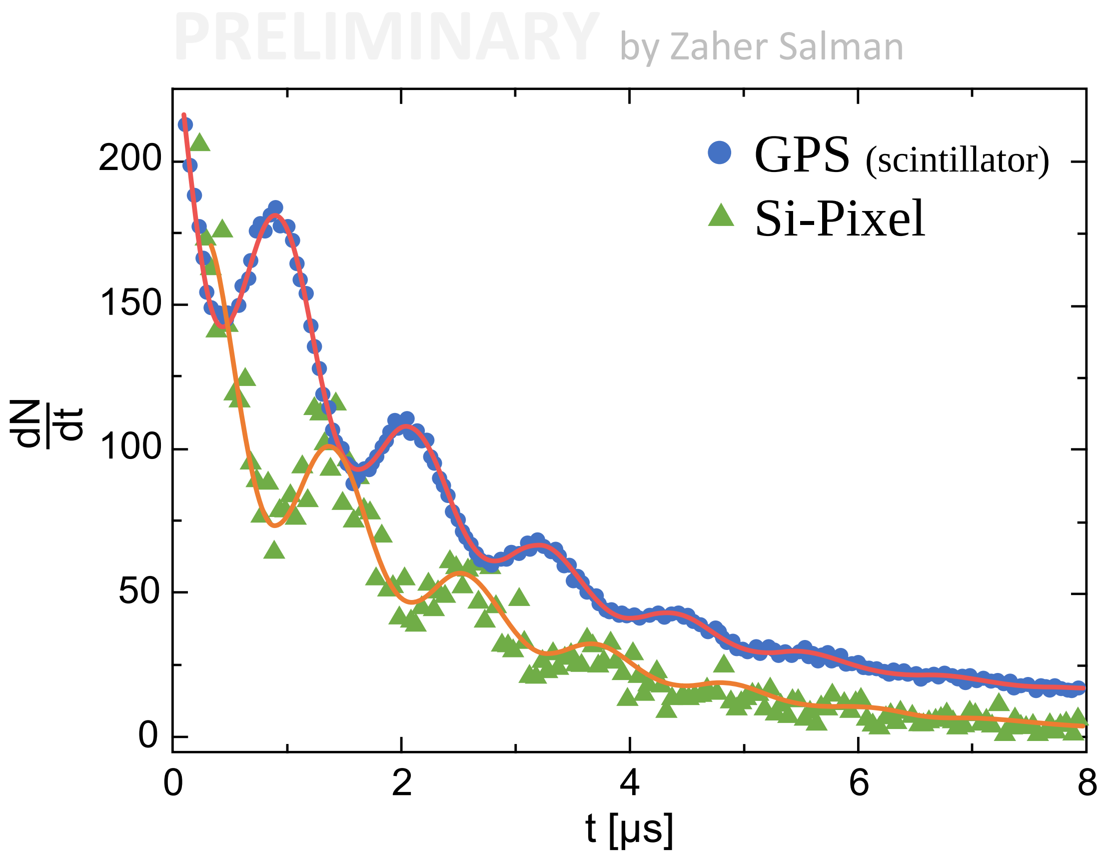

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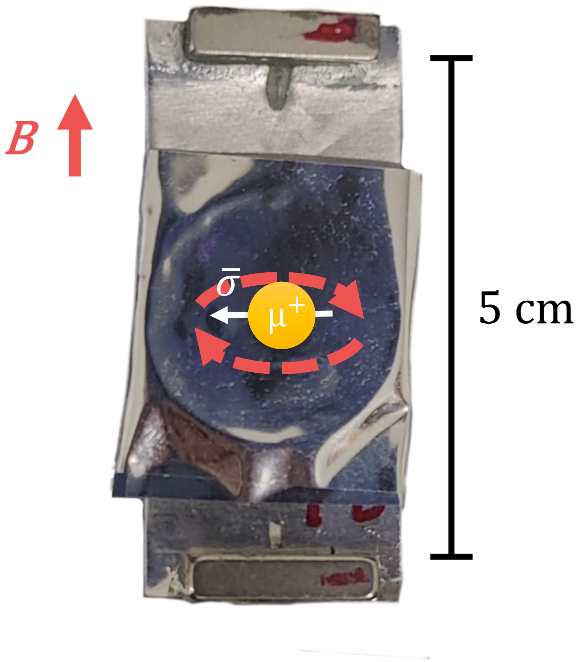

- Results
  - Low statistics (3 s)
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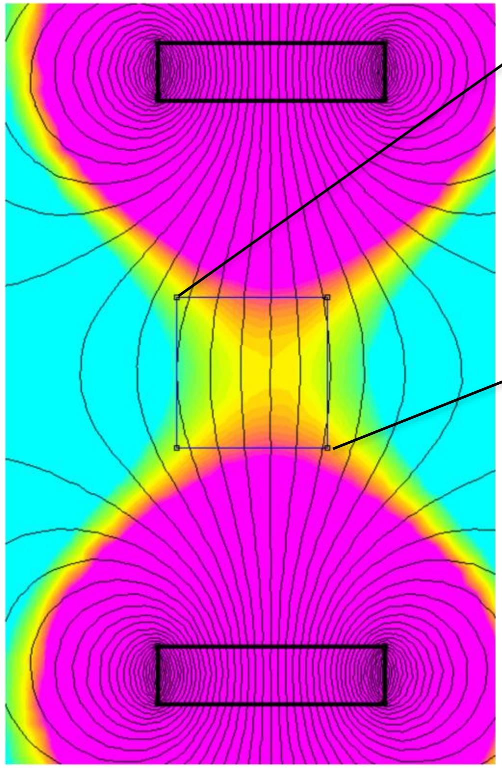
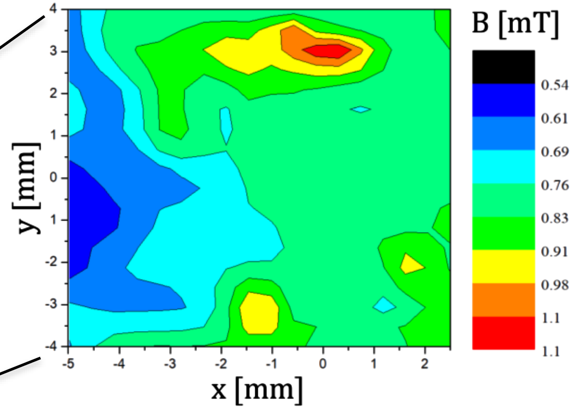
  - Negligible background

Magnetic field mapping

PRELIMINARY by Zaher Salman



Simulation



Data

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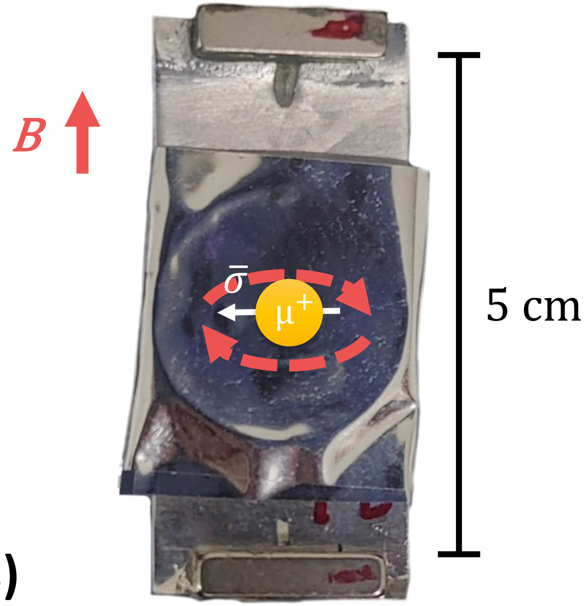

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  - **Low statistics (3 s)**
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  - Combined vertex and spin measurement

Results

Magnetic field mapping

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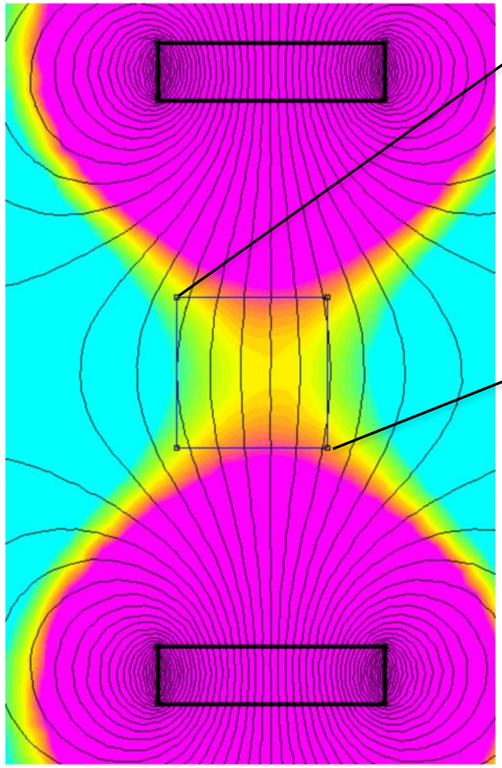

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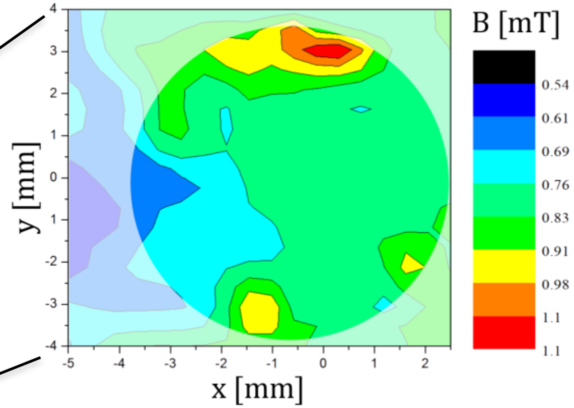

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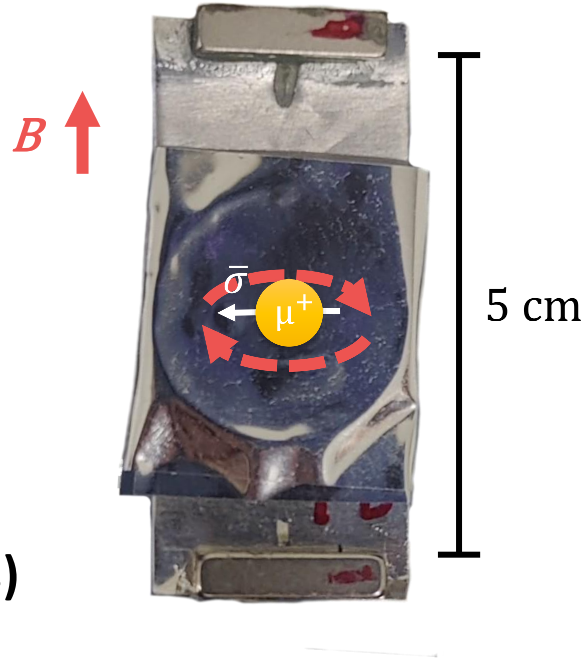

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Conclusion

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☑ Successful proof-of-concept

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- ☐ Further data analysis needed ⇨ increase statistics & setup characterization

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  - large beam diameter

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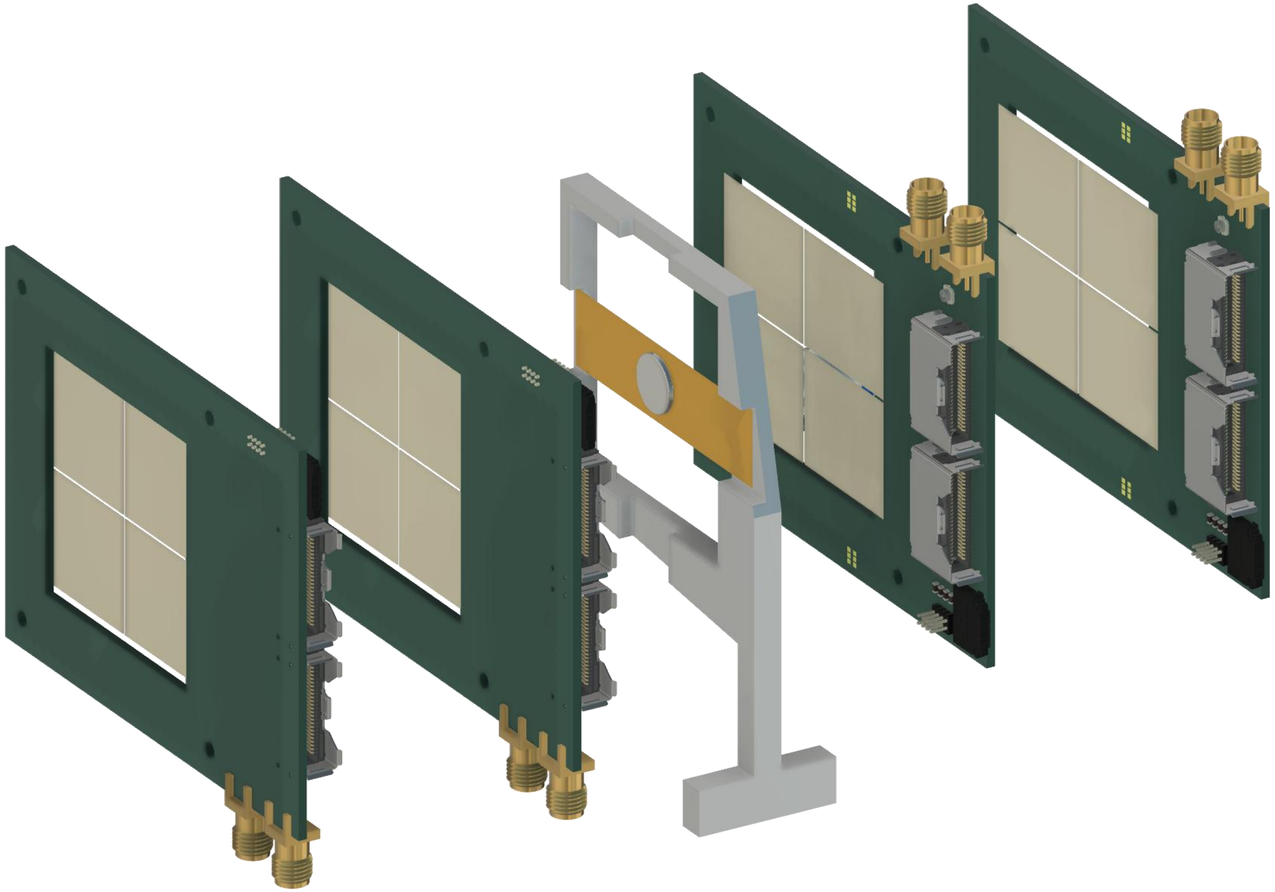
Thanks!

Backup

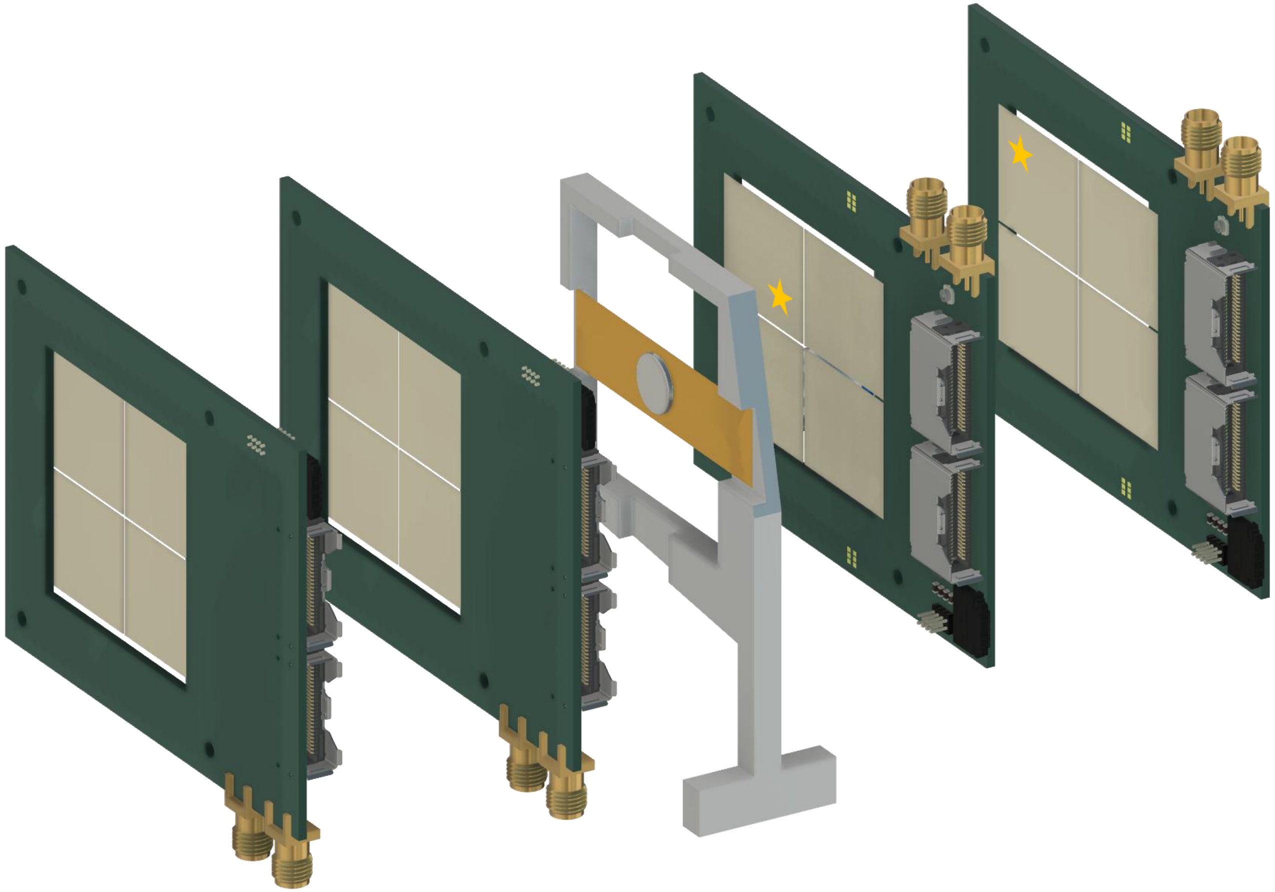
µSR Setup

Tracking



μSR Setup

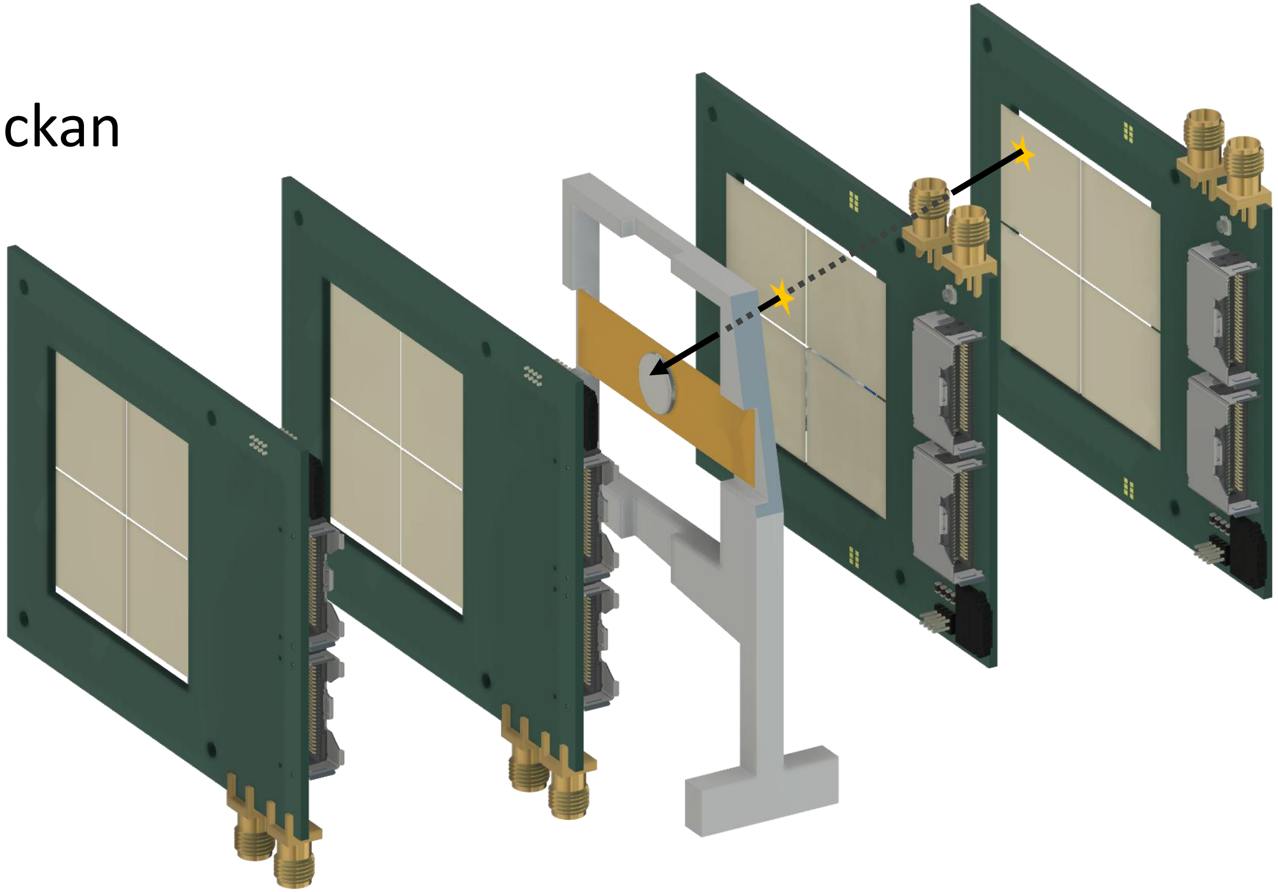
Tracking



µSR Setup

Tracking

- Tracklet matching with Corryvreckan



µSR Setup
Tracking

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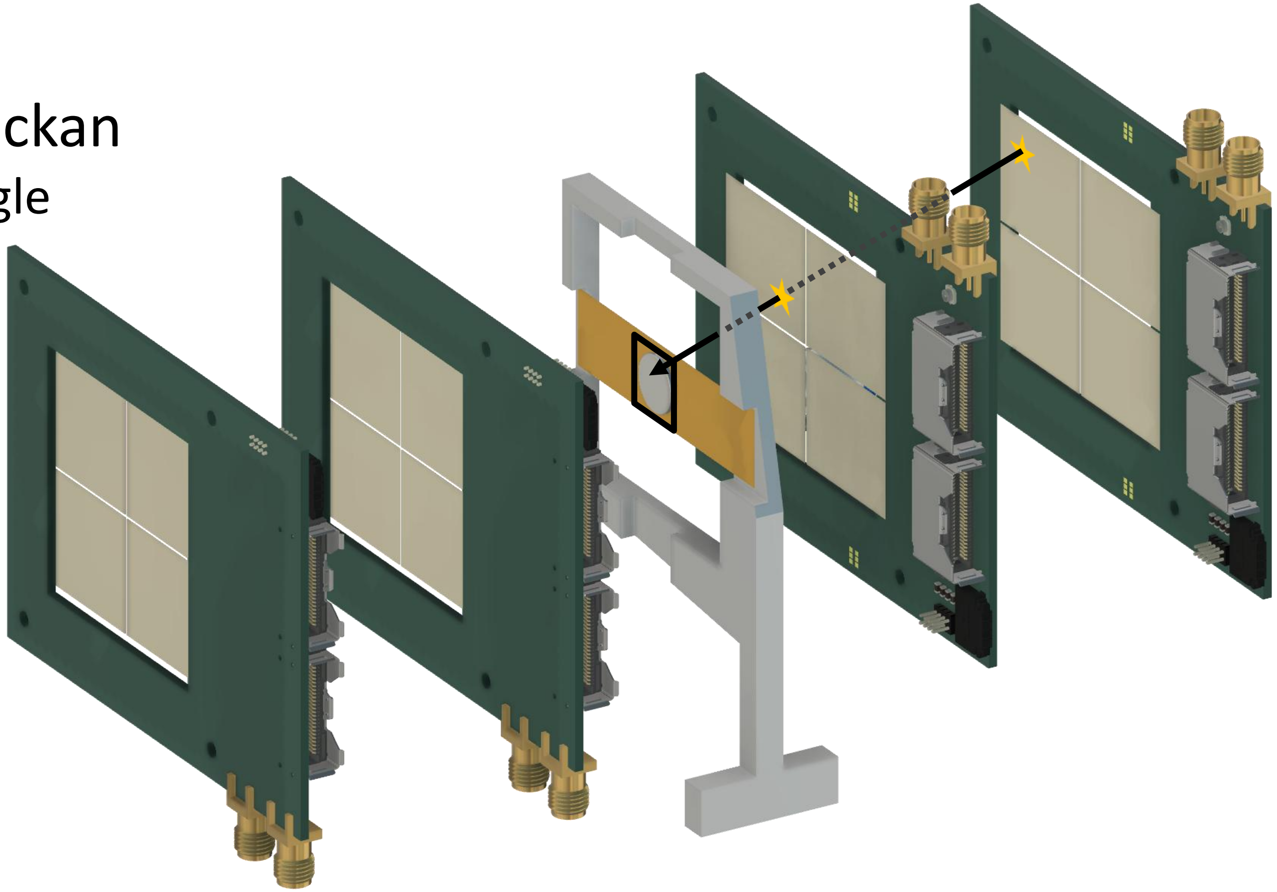

μSR Setup
Tracking

- Tracklet matching with Corryvreckan
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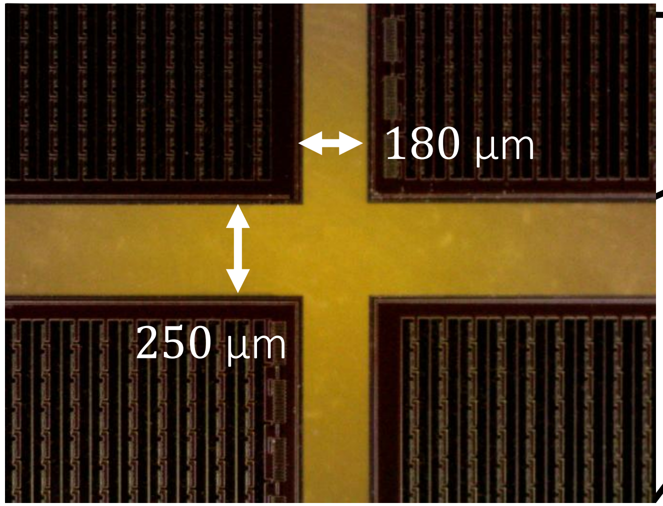

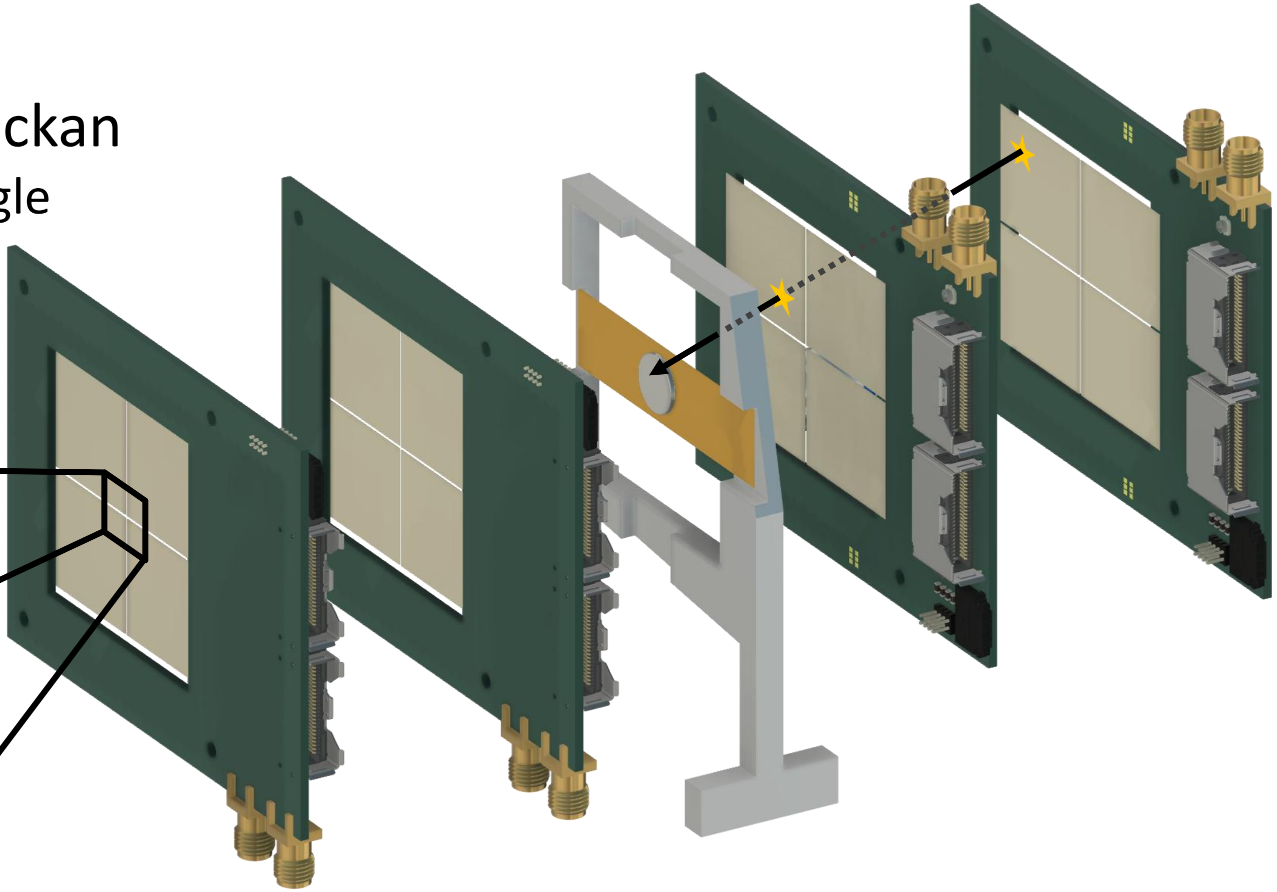

μSR Setup

Tracking

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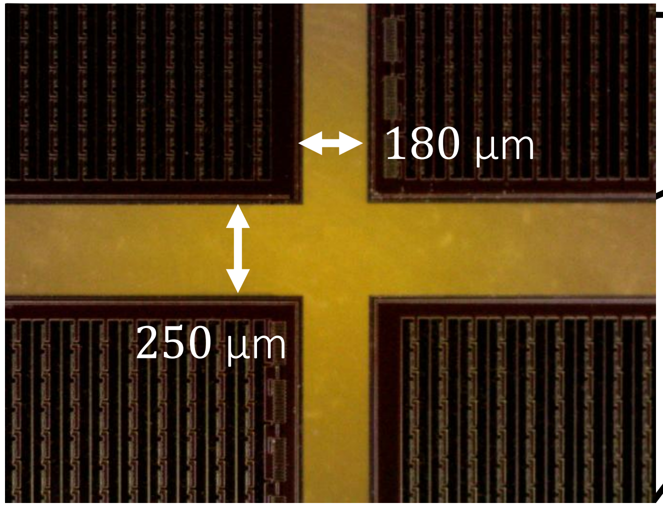

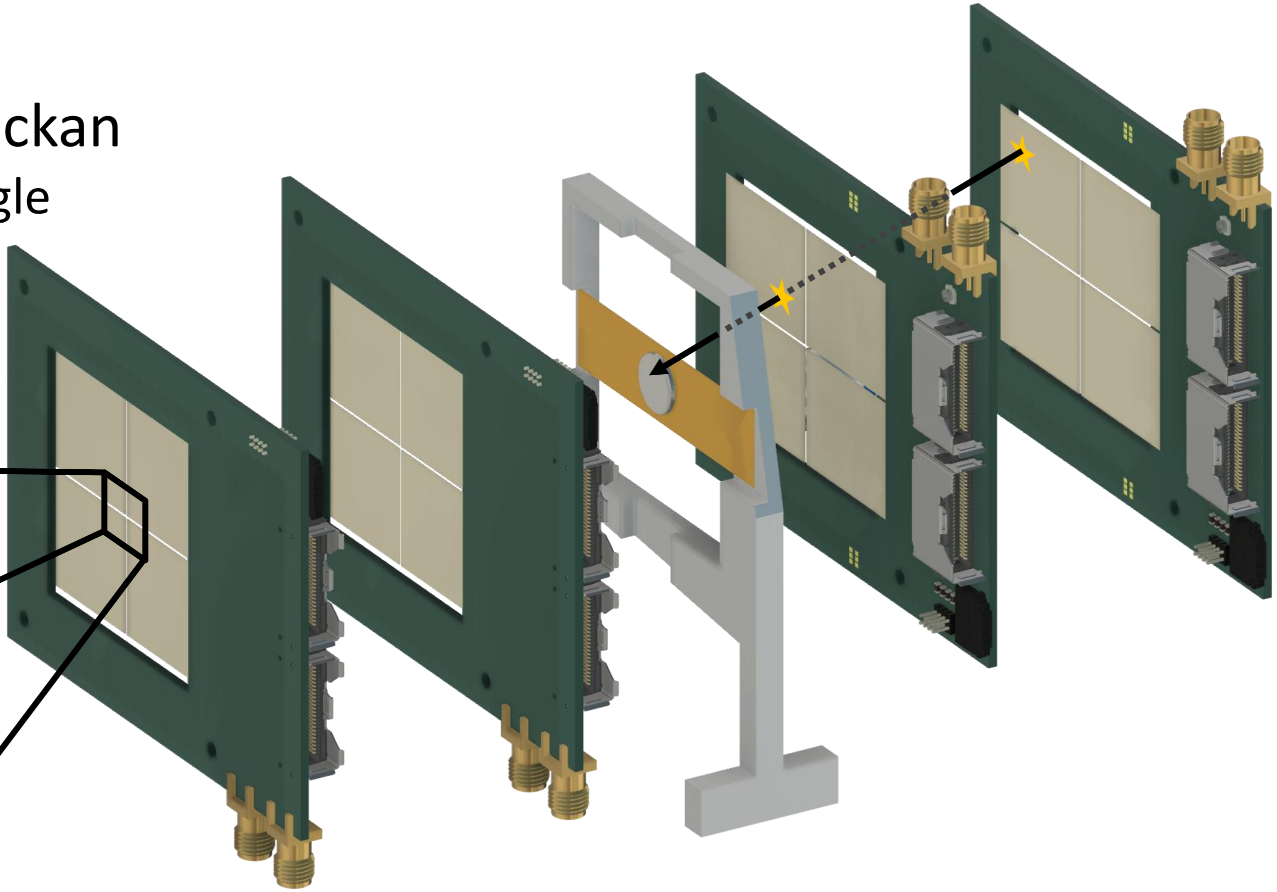

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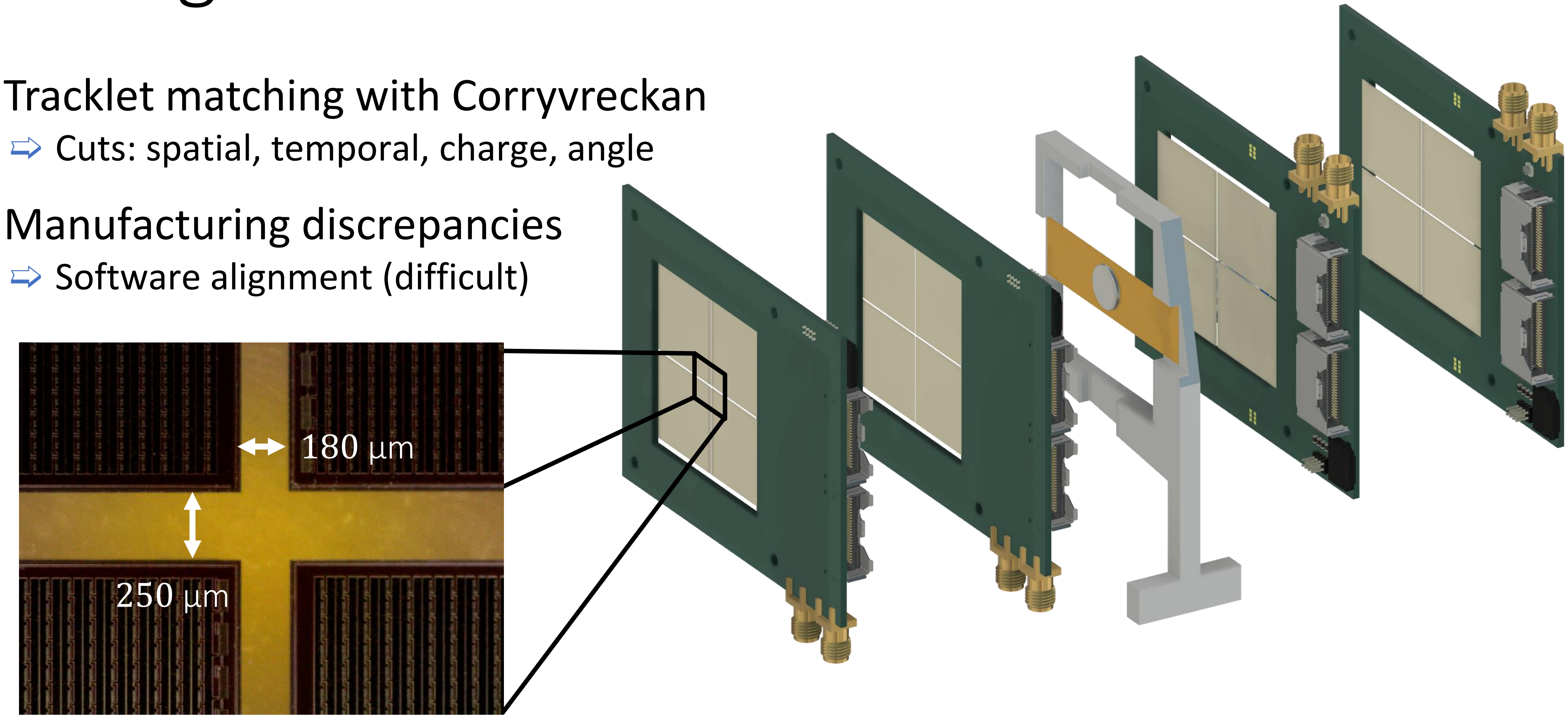

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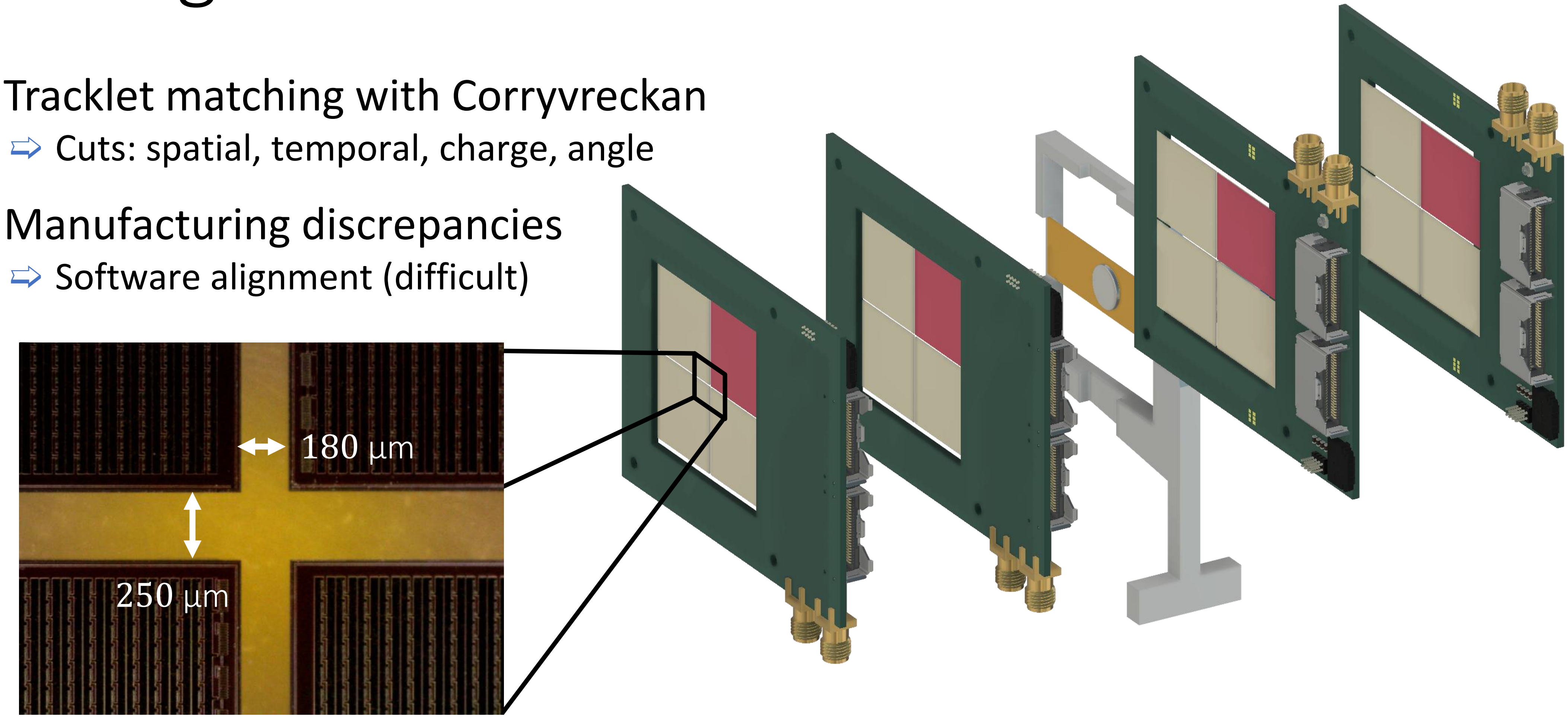

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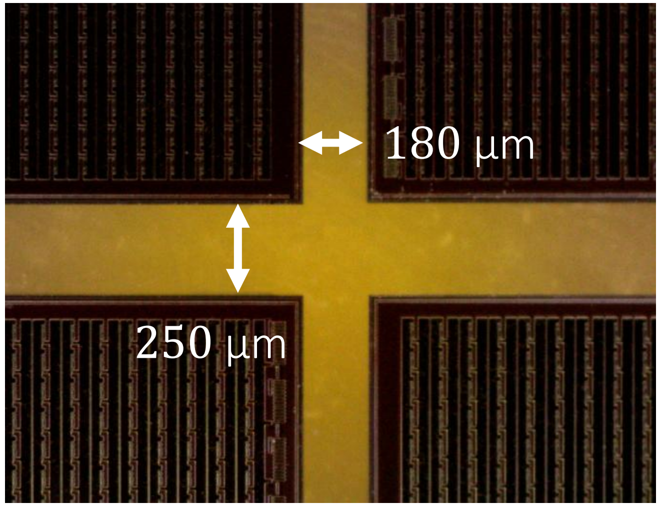

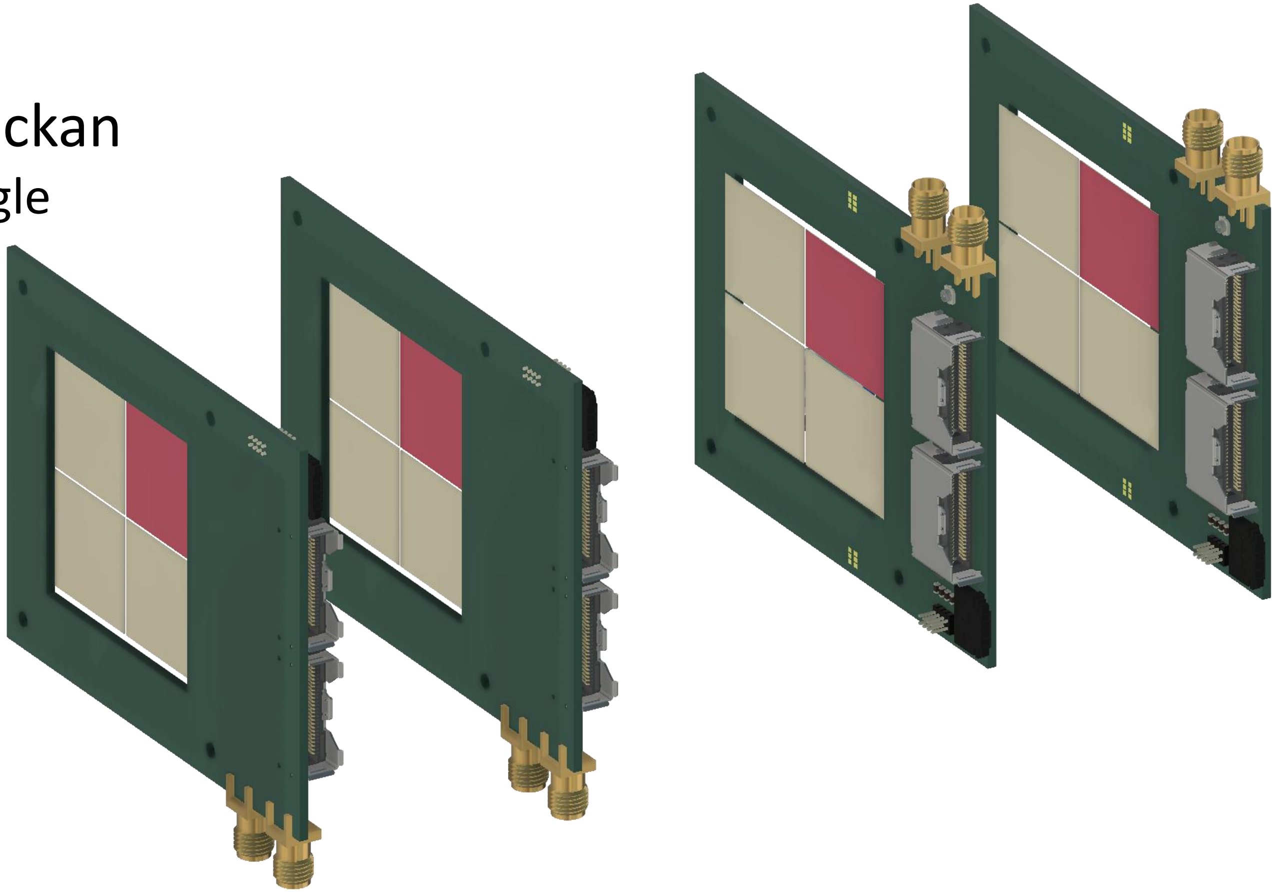

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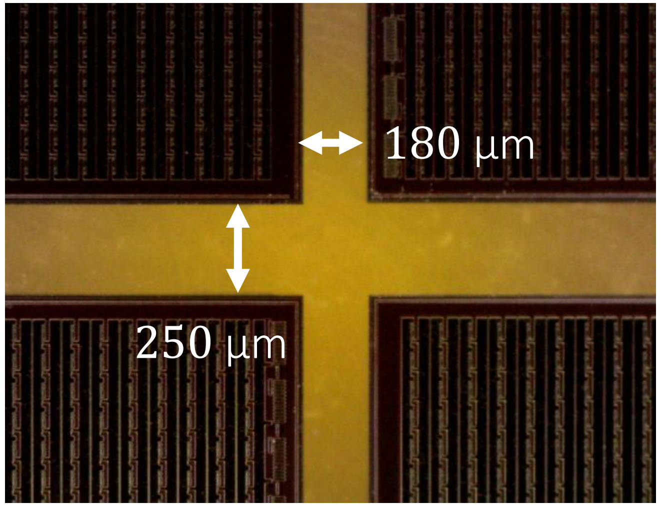

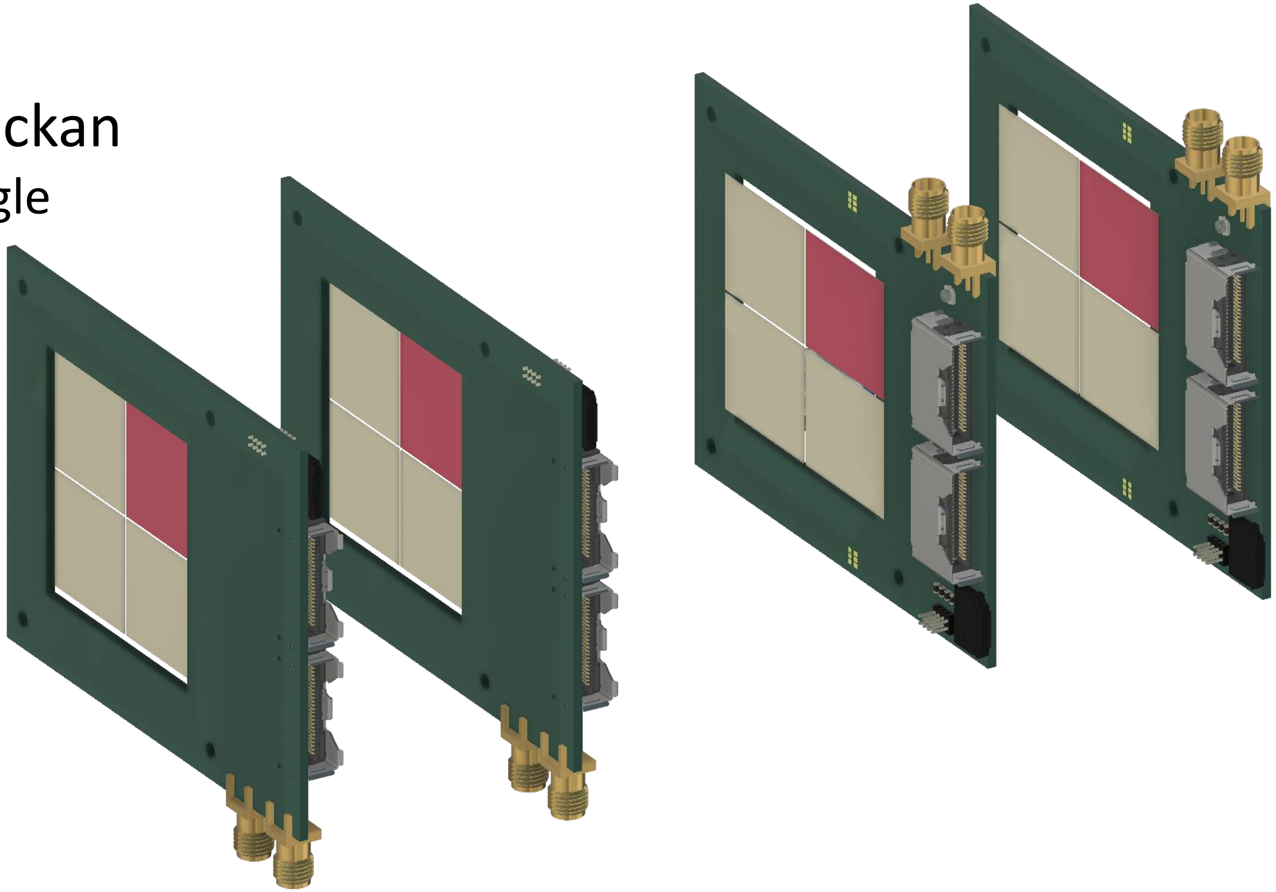

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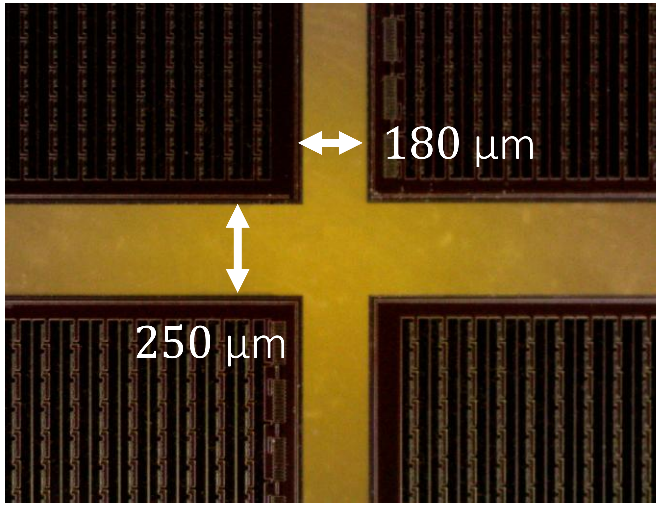
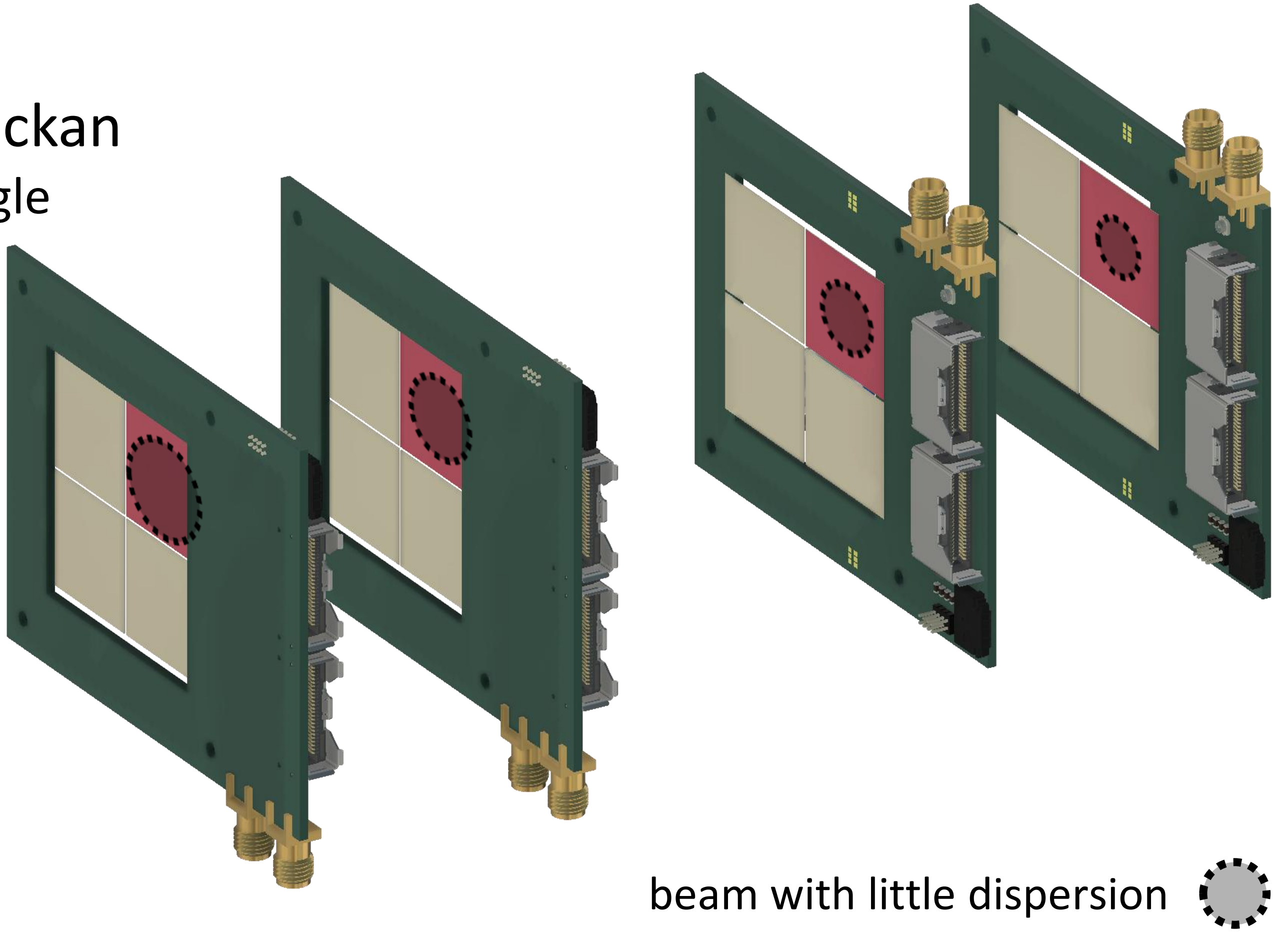




µSR Signal

Positron rate: $N(t)/dt = B_0 + N_0 \cdot \exp\left(-t/\tau_\mu\right) \cdot \left[1 + A_0 G_\perp(t)\, cos\left(\bar{\boldsymbol{\omega}}_\mu t + \phi\right)\right]$

Background

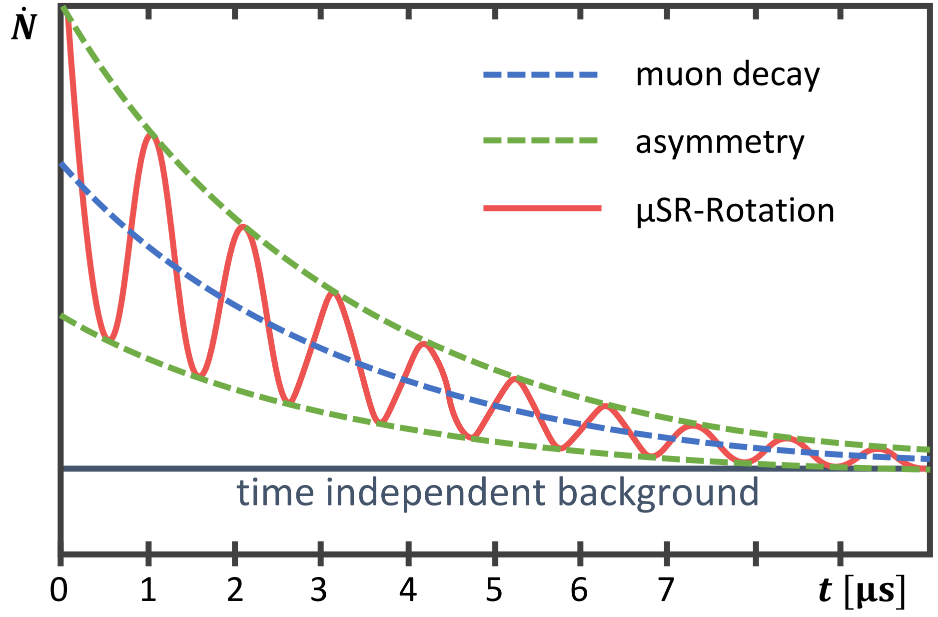
Exponential muon **decay**

Intrinsic asymmetry parameter of weak decay

Relaxation function of temporal decrease of the polarization degree

Angle between positron and muon spin direction

Larmor frequency of muon spin precession: $\bar{\boldsymbol{\omega}}_\mu = \gamma_\mu \cdot (B_{\text{ext}} + \langle B_{\text{int}} \rangle)$



Positron detector in a fixed direction

$\gamma_\mu = g_J \cdot \frac{q}{2m}$ $\qquad \bar{\mu} = \gamma_\mu \cdot \bar{\sigma}_\mu$

Positron detector
$N(t)/dt$