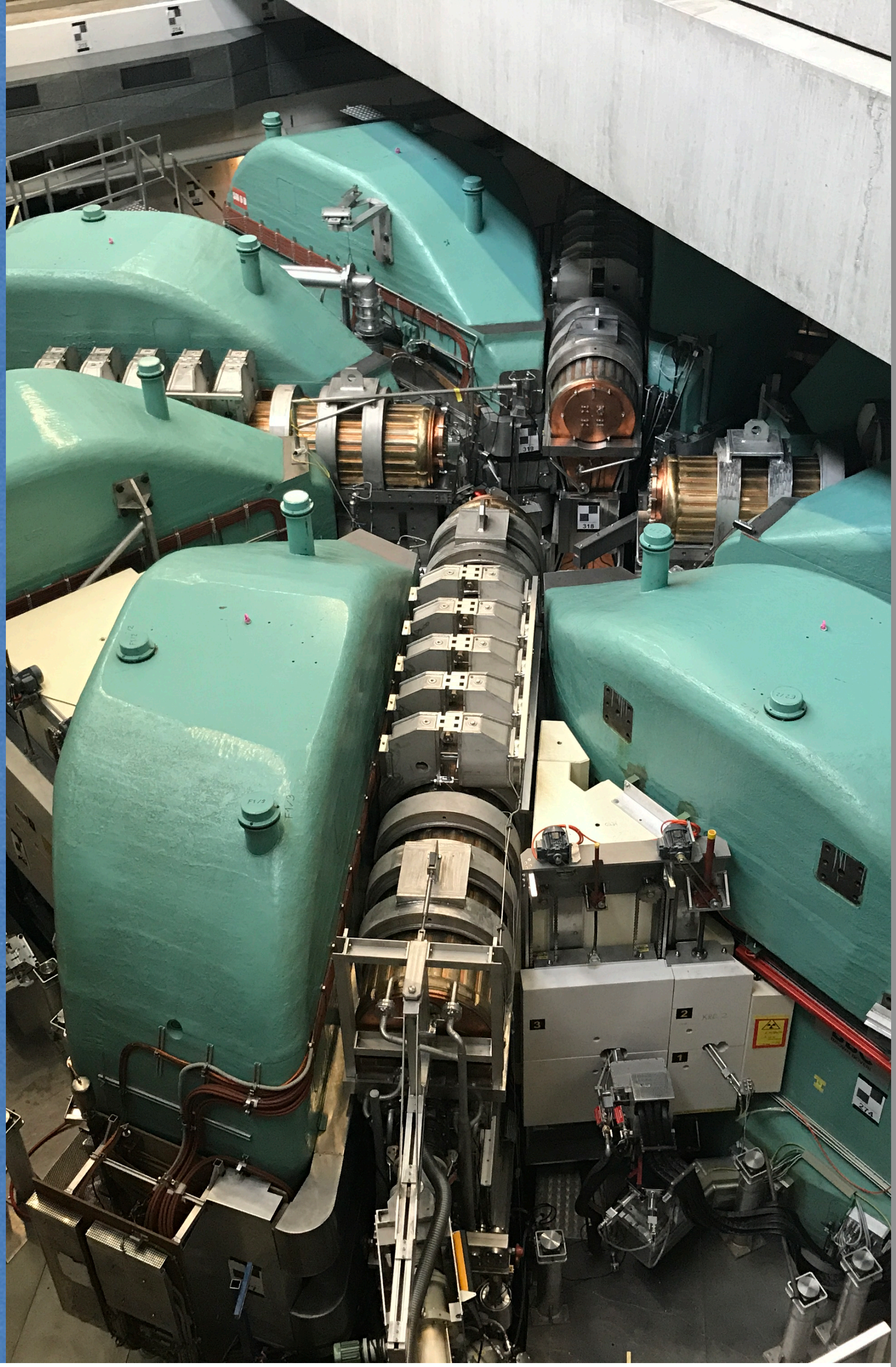
# R&D towards the Muon EDM Search at PSI:

## Beam characterisation and detector studies



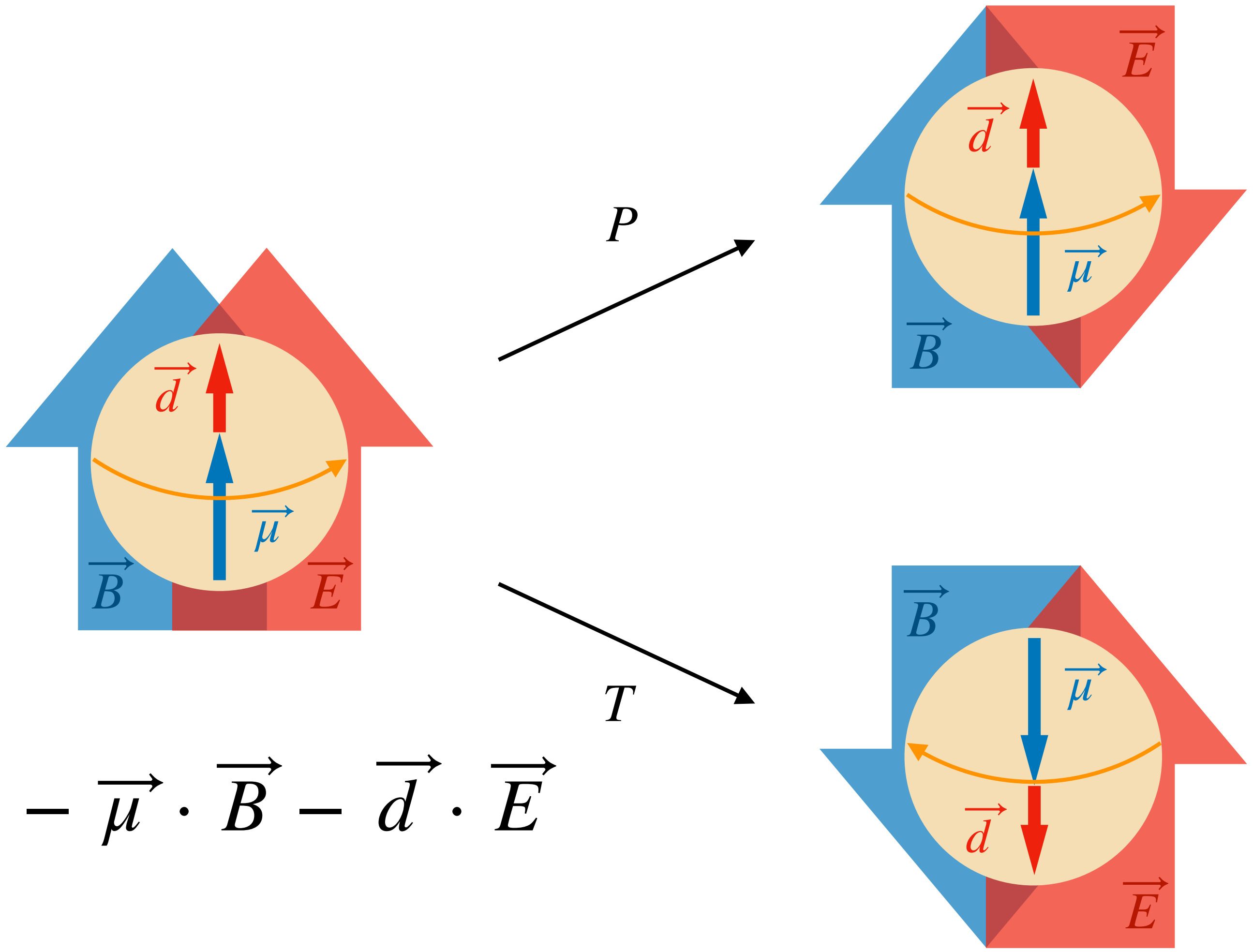


Mikio Sakurai ETH zürich / PAUL SCHERRER INSTITUT PSI

msakurai@phys.ethz.ch

10/10/2019 | Zurich PhD seminar 2019, PSI

# EDM & CP violation




$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

- A non-zero particle EDM violates P and T
- Assuming CPT invariance, T violation implies CP violation

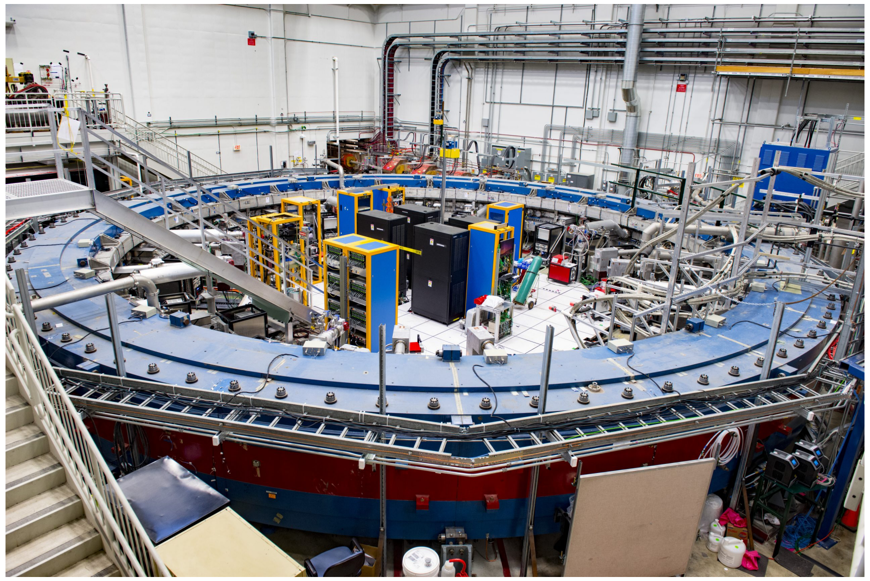
⇒ **Indication of new physics**

  - Additional CP violation sources
  - Explanation for the matter-dominated Universe

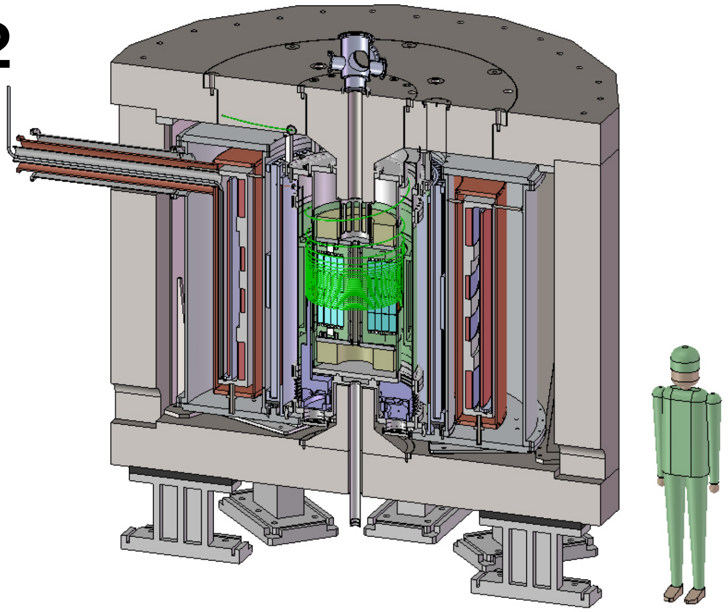
# The muon EDM



**FNL g-2**



**J-PARC g-2**



- Always measured in the g-2 storage rings as a by-product
- Current limits
  - BNL g-2 experiment:

    $$1.8 \times 10^{-19} e \cdot \mathrm{cm}\ (95\,\%\,\mathrm{C.L.})$$

  - SM: $\simeq 10^{-36} e \cdot \mathrm{cm}$
  - BSM: up to $\simeq 3 \times 10^{-22} e \cdot \mathrm{cm}$
- One of the least tested area of SM

\+ Observed tension with SM

  - B decays
  - g-2 of electron & muon

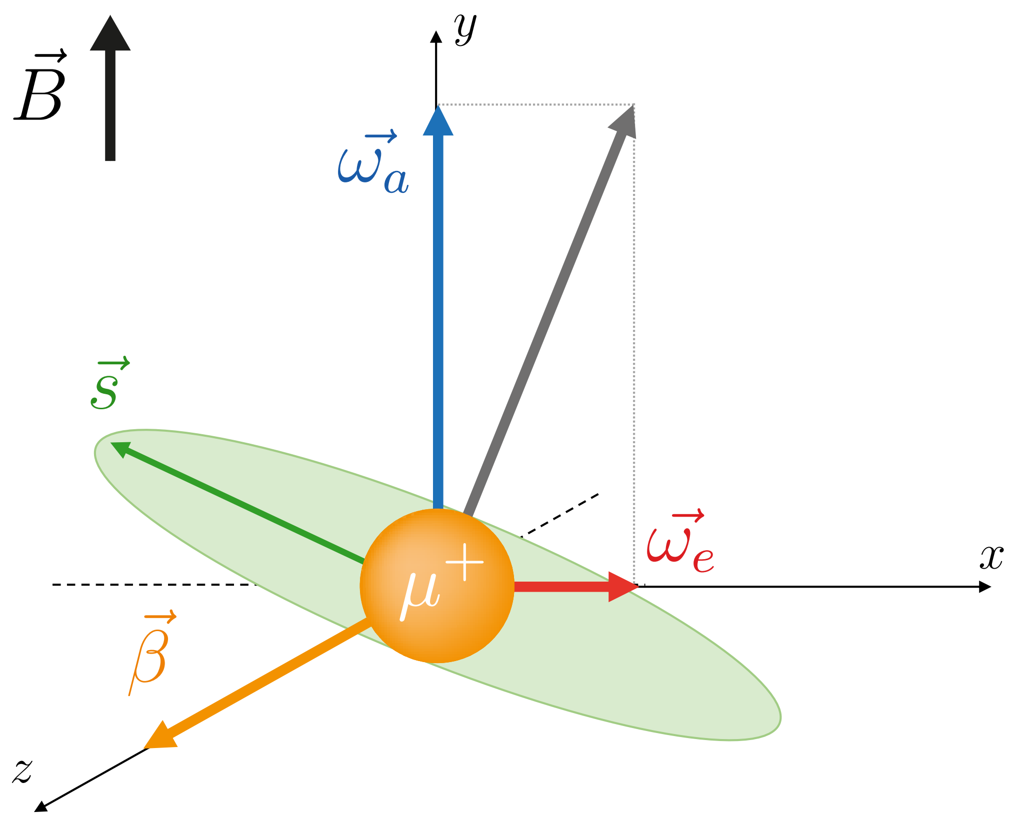
**The first dedicated muon EDM search is attractive!**

# Muon spin precession in B- and E-field



**MDM** **EDM**

$$\frac{d\vec{s}}{dt} = -\underbrace{\frac{e}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\vec{\omega}_a} + \underbrace{\frac{e}{m}\left[-\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]}_{\vec{\omega}_e}$$




- $\vec{\omega}_a$ : spin precession in orbital plane ("g-2" precession)
- $\vec{\omega}_e$ : spin precession out of orbital plane ("EDM" precession)

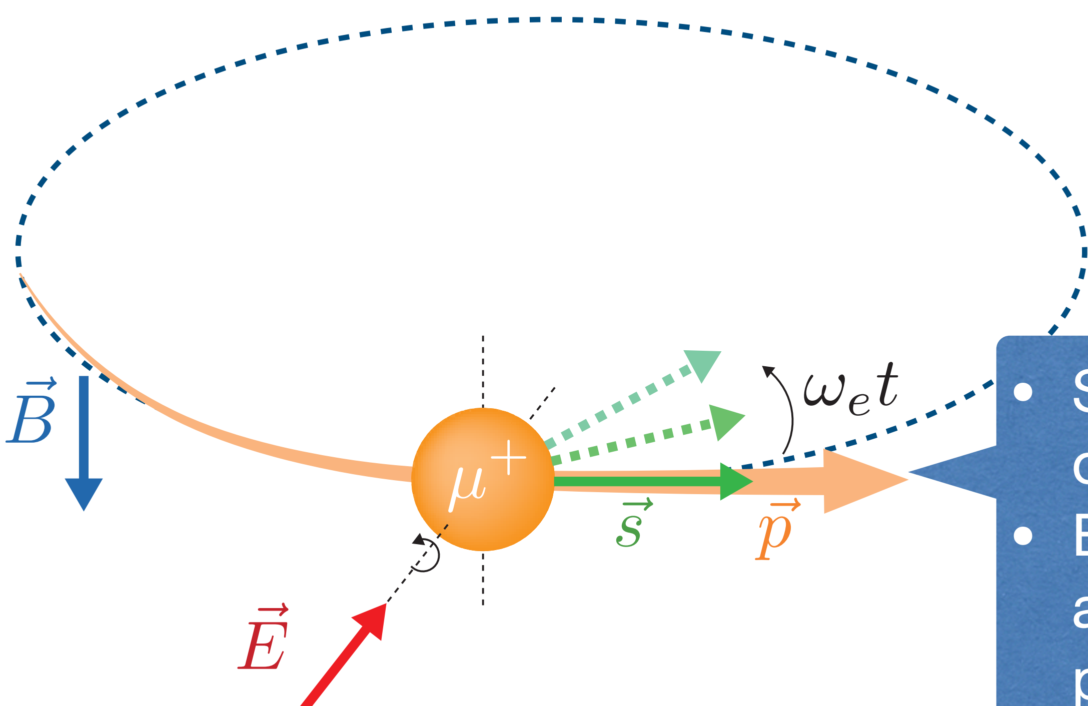
# Muon EDM search with frozen-spin technique

- Cancel “g-2” precession by applying a radial E-field: Frozen-spin condition $E \approx aBc\beta\gamma^2$

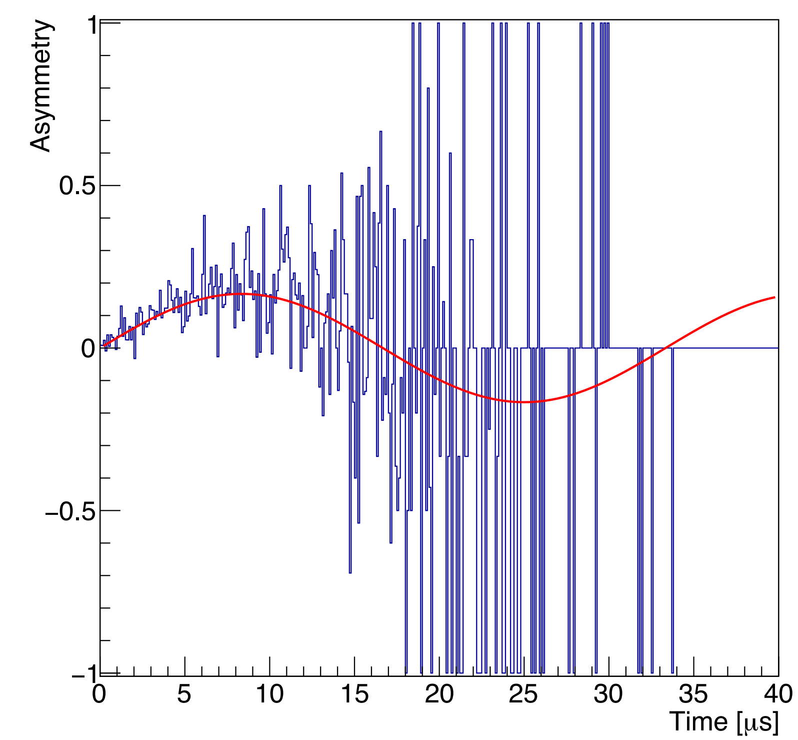
**MDM** | **EDM**

$$\frac{d\vec{s}}{dt} = -\frac{e}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{e}{m}\left[-\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$\vec{\omega}_a = 0$ | $\vec{\omega}_e$

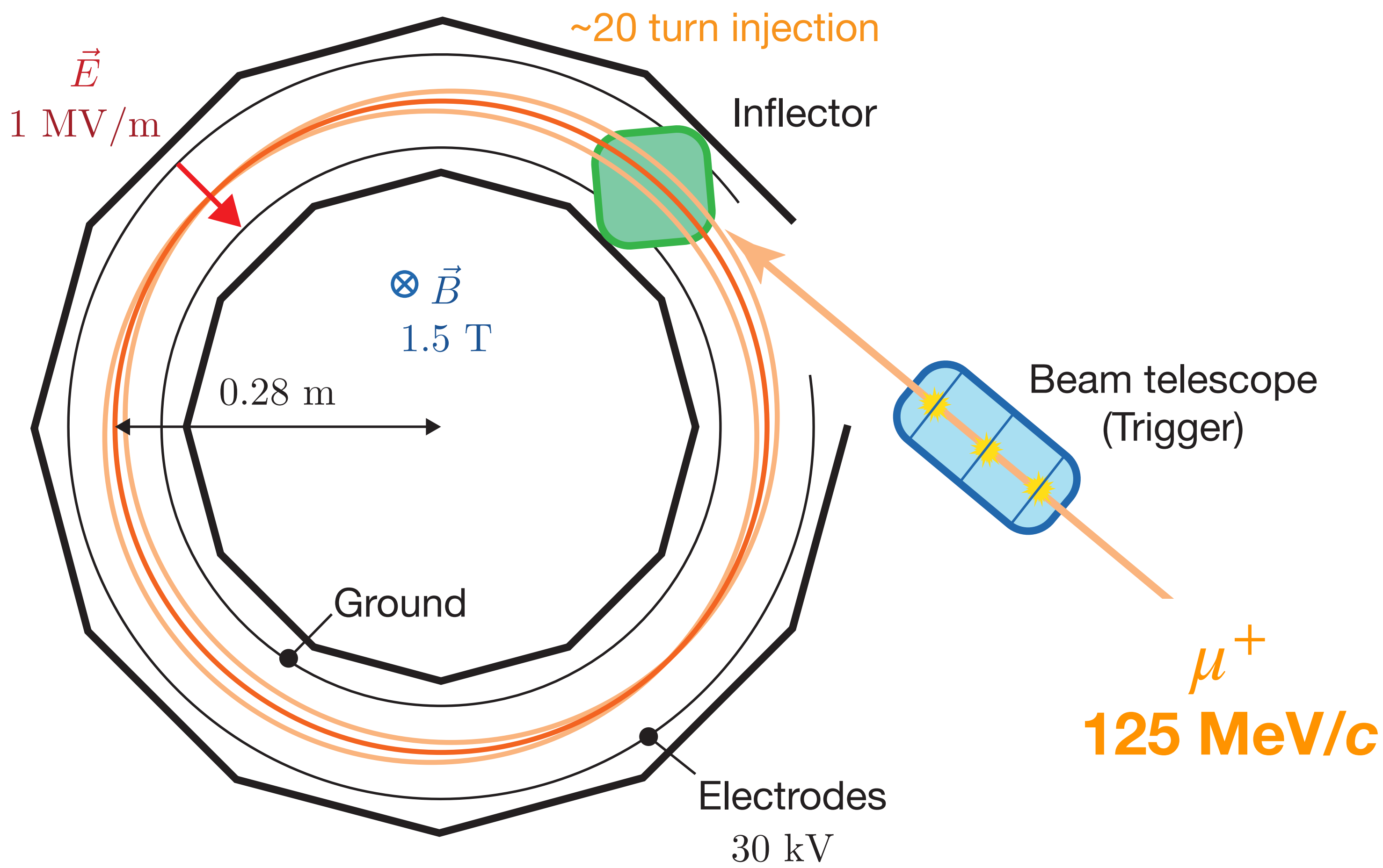


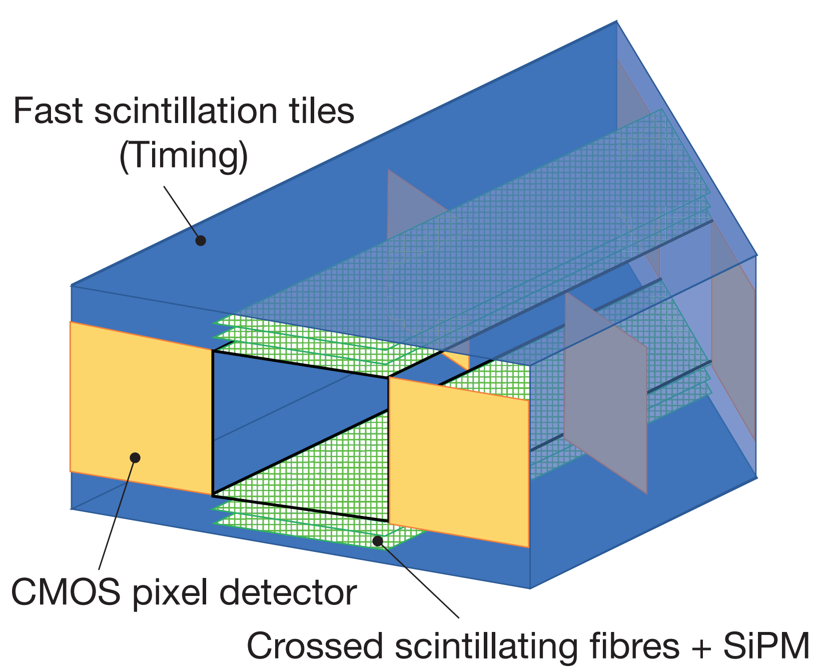

- Spin remains parallel on the orbit
- EDM signal is visible as growing vertical polarisation



# Muon EDM search at PSI





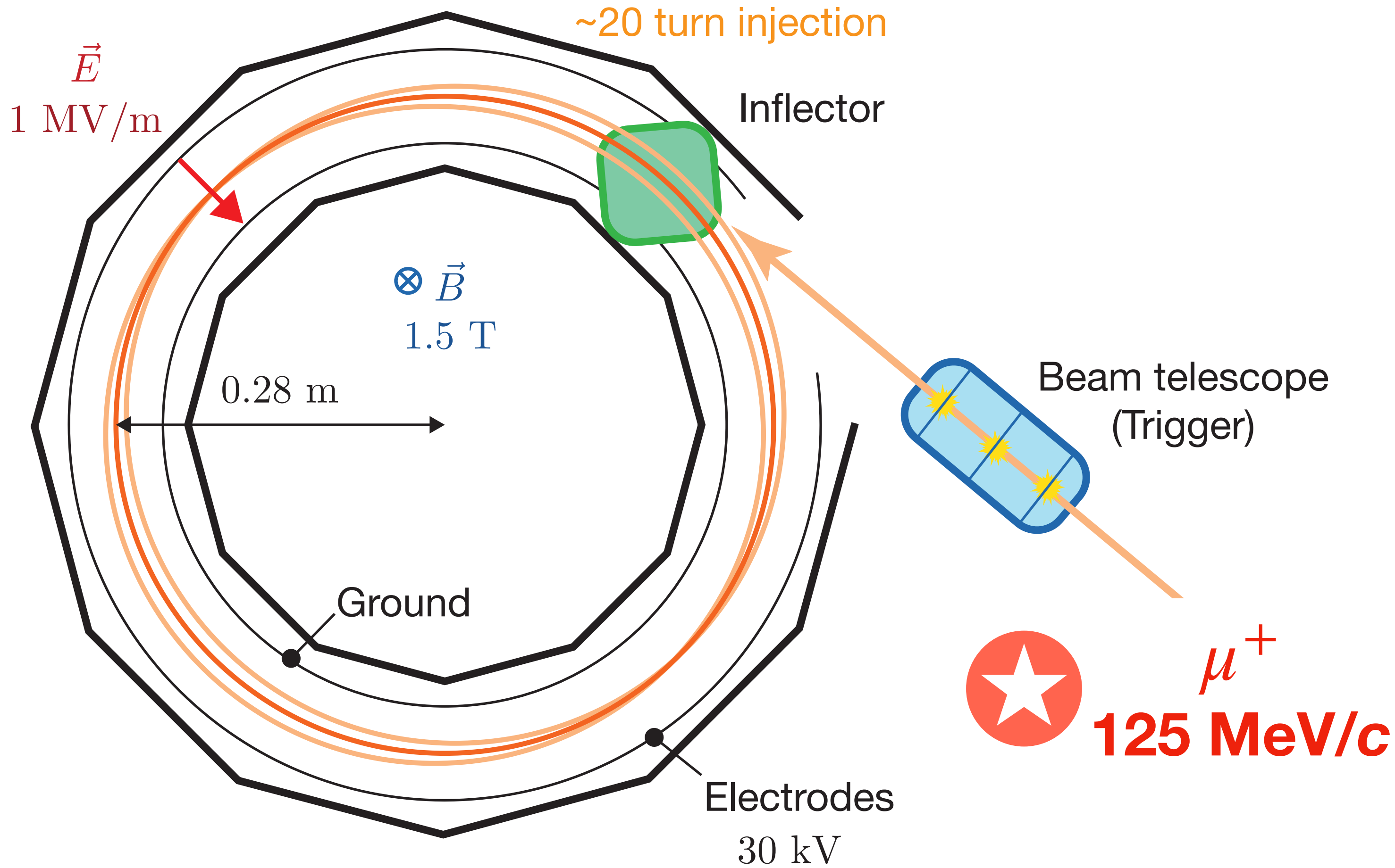

1. Use 125 MeV/c polarised $\mu^+$ beam from PSI μE1 beam line
2. Beam telescope triggers $\mu^+$ & start ramping of inflector
3. Store one $\mu^+$ at a time ~200 kHz rate
4. Detect $e^+$ from $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ with tracking detector

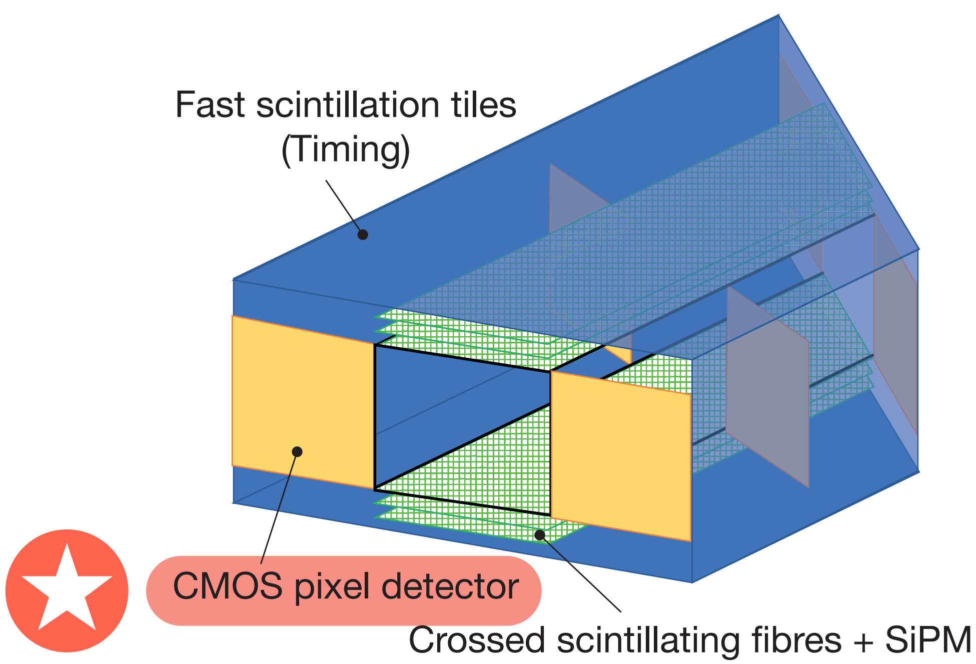
- Expected sensitivity (1 year, $N = 4 \times 10^{-14}$ muon decays)

$$\sigma_{d_\mu} = \frac{\hbar \gamma a}{2 \tau E \alpha P \sqrt{N}} = 5 \times 10^{-23} e \cdot \mathrm{cm}$$

# Muon EDM search at PSI



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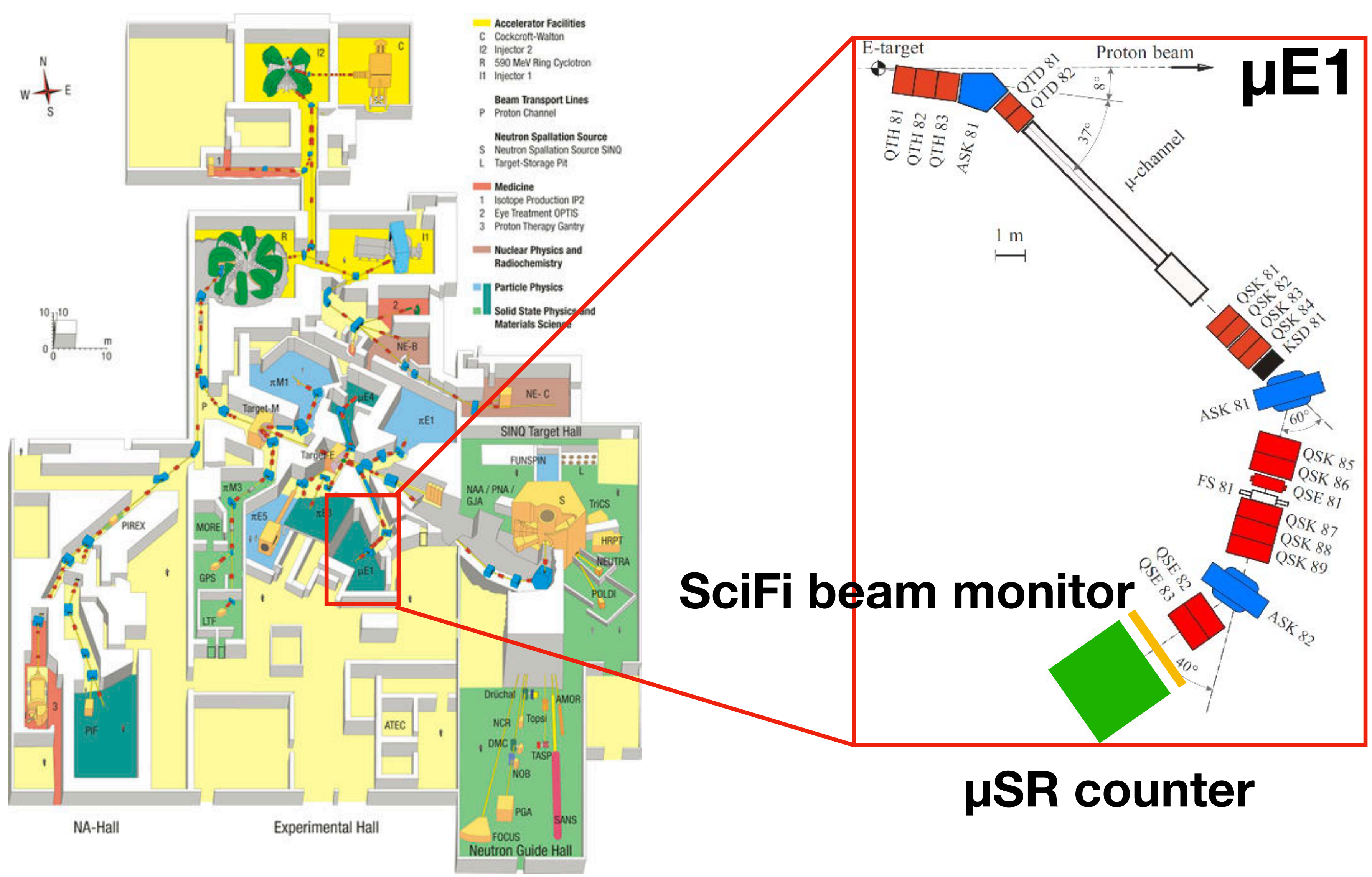
# Beam characterisation at µE1 beam line

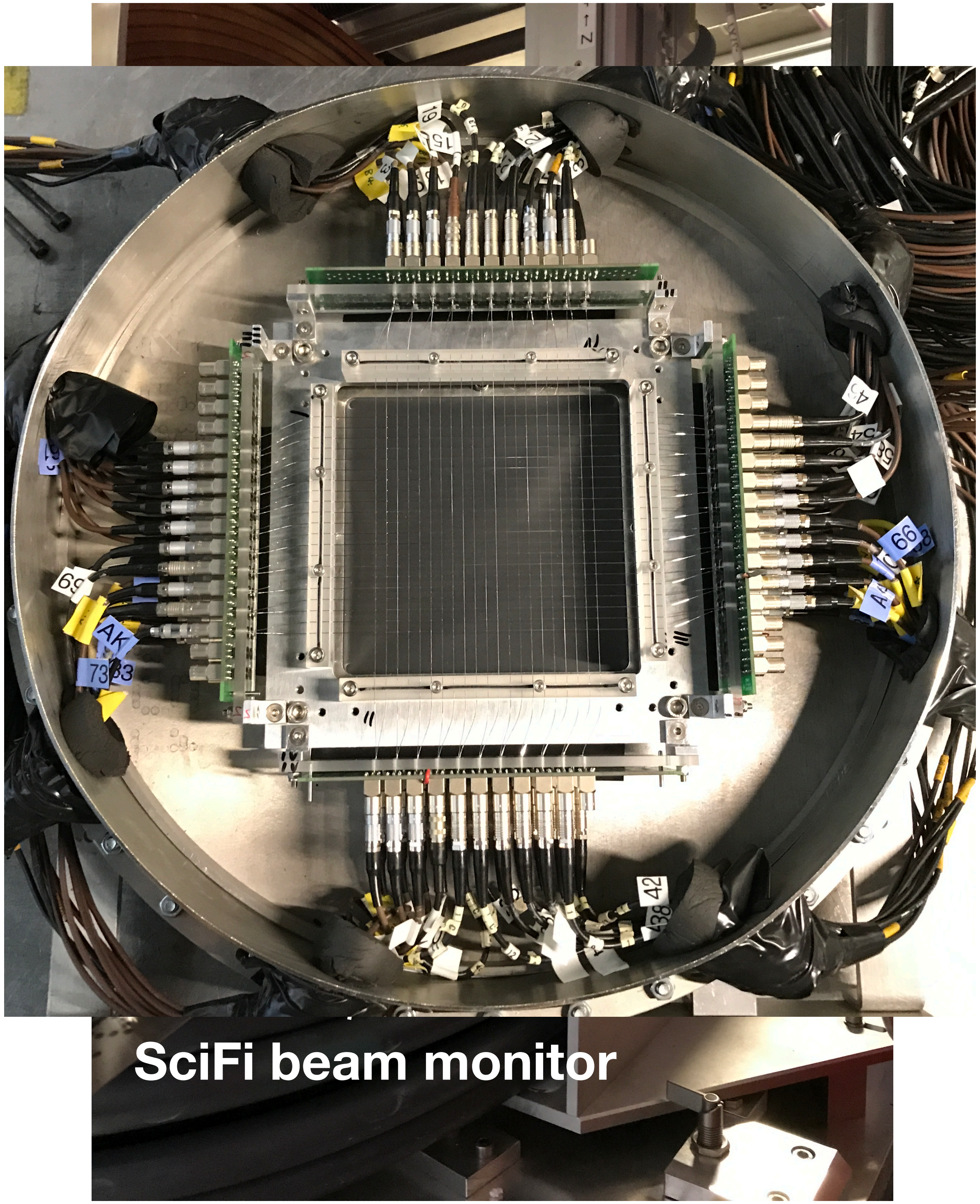


- Motivation: Obtain essential input parameters for simulations of the experiment
- Studied for two beam tunes up to 125 MeV/*c*
  - Phase space measurement with SciFi beam monitor
  - Polarisation measurement with µSR counter



# Phase space measurement





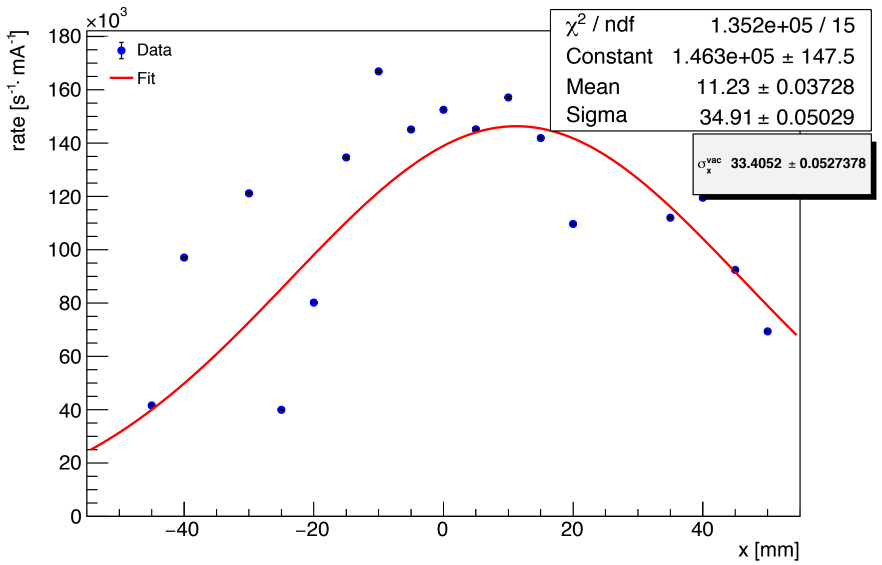
SciFi beam monitor

- Phase space can be determined with "quadrupole scan"
  - Use quadratic relationship between the focusing strength of a quadrupole and beam size
- Strategy:
  Measure beam size with varying the focusing strength
- SciFi beam monitor is able to measure
  - Beam size
  - Beam rate

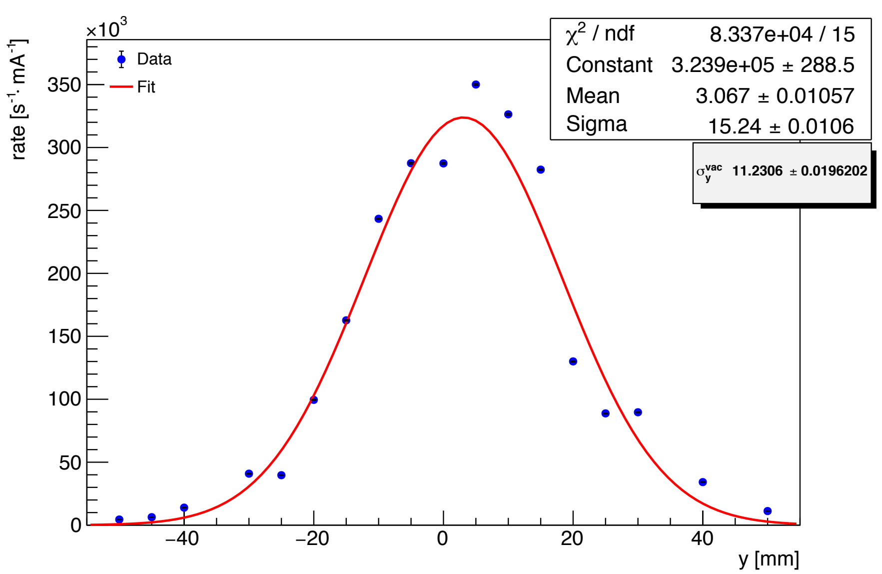
# Beam size/rate measurement at 125 MeV/c

## $\mu^+$ rate: $4.9 \times 10^7$ Hz/mA

### New tune - horizontal

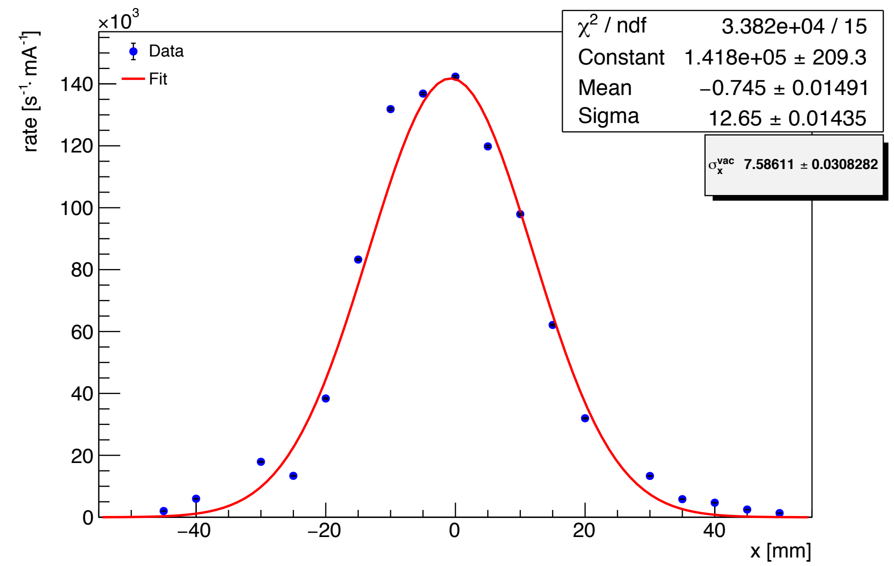



### New tune - vertical

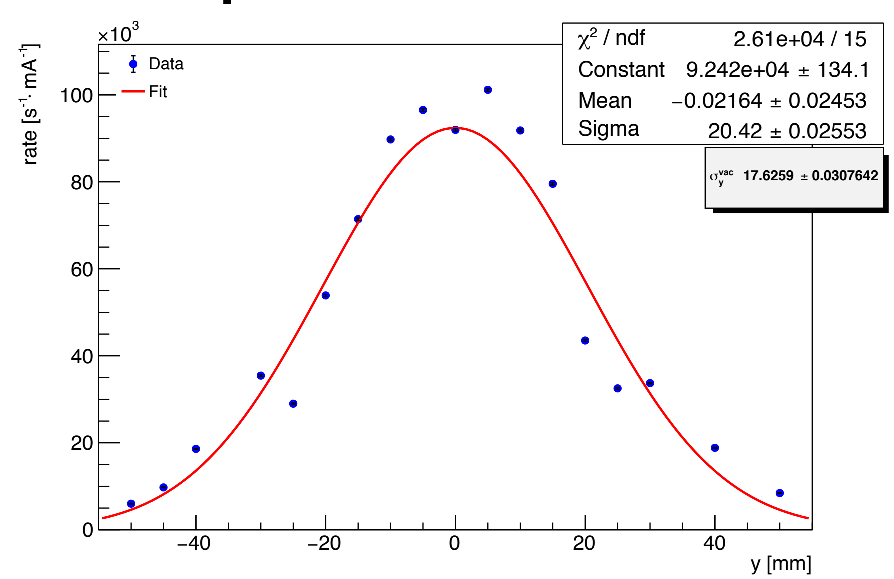



## $\mu^+$ rate: $1.9 \times 10^7$ Hz/mA

### μSR tune - horizontal



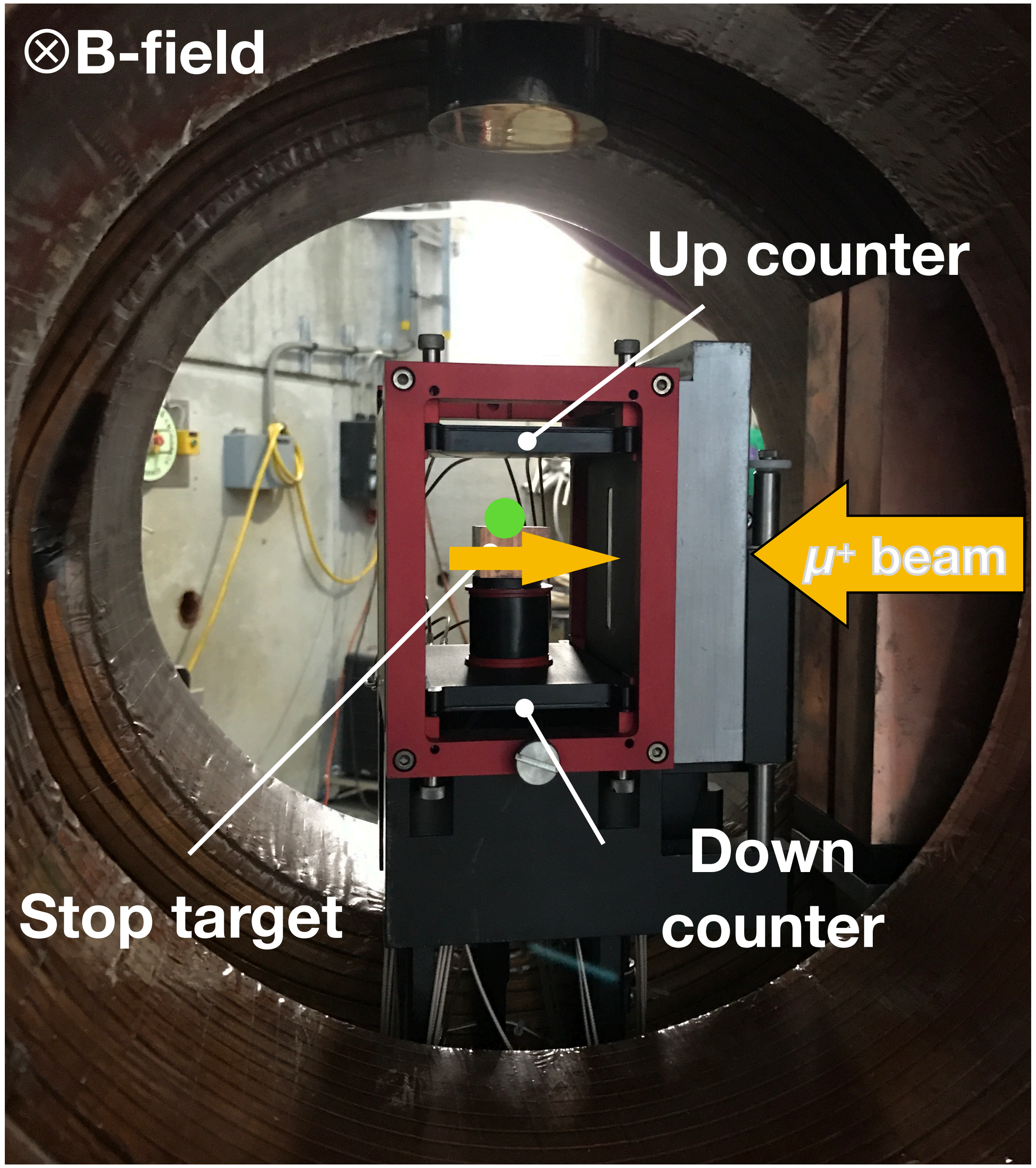

### μSR tune - vertical




- Phase space analysis is ongoing

# Polarisation measurement

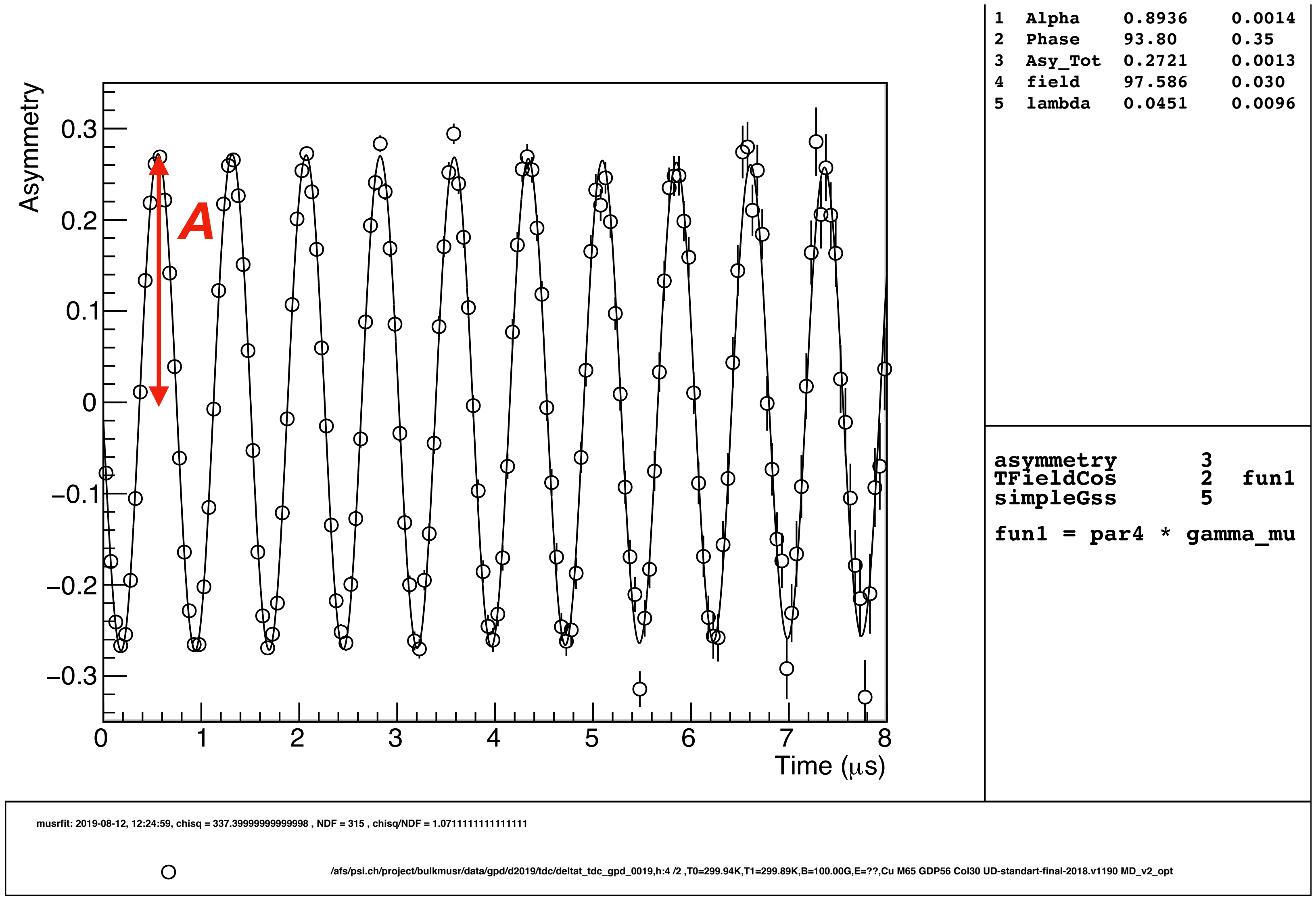





- Polarisation of muon can be determined using μSR technique
  - Polarised $\mu^+$ stop at target
  - Under external B-field, $\mu^+$ spin precess with Larmor frequency
  - Monitor time evolution of $\mu^+$ spin via decay $e^+$
- Strategy:
  Plot up-down $e^+$ counting asymmetry and compare its amplitude with P=100% simulation

# Polarisation measurement at 65 MeV/c

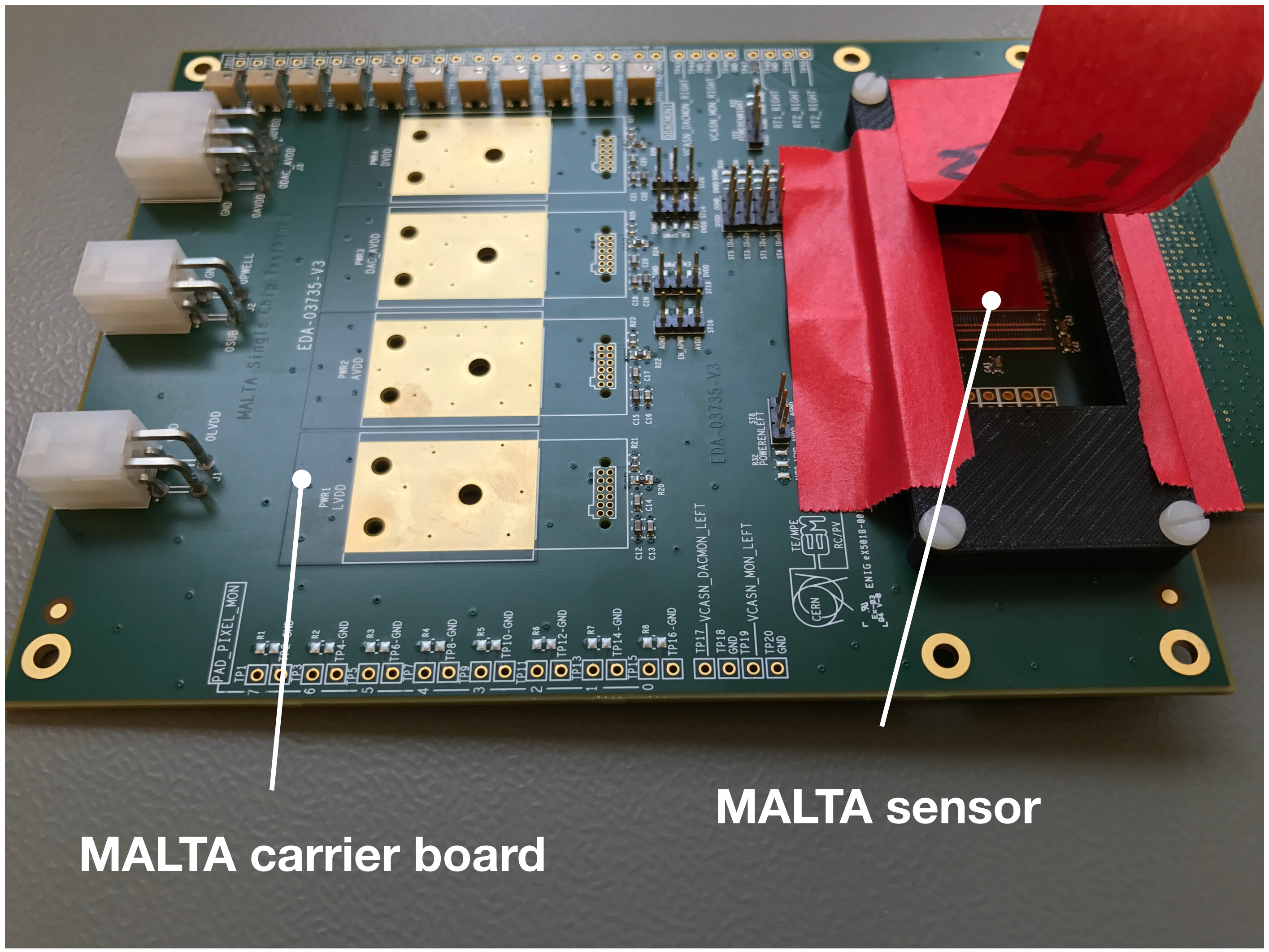
## Cu target@65 MeV/c, 20 mins




- Amplitude of up-down asymmetry, *A*, is compared with P=100% simulation to determine polarisation
- Together with phase space measurement, analysis is ongoing

# Detector study at ETH



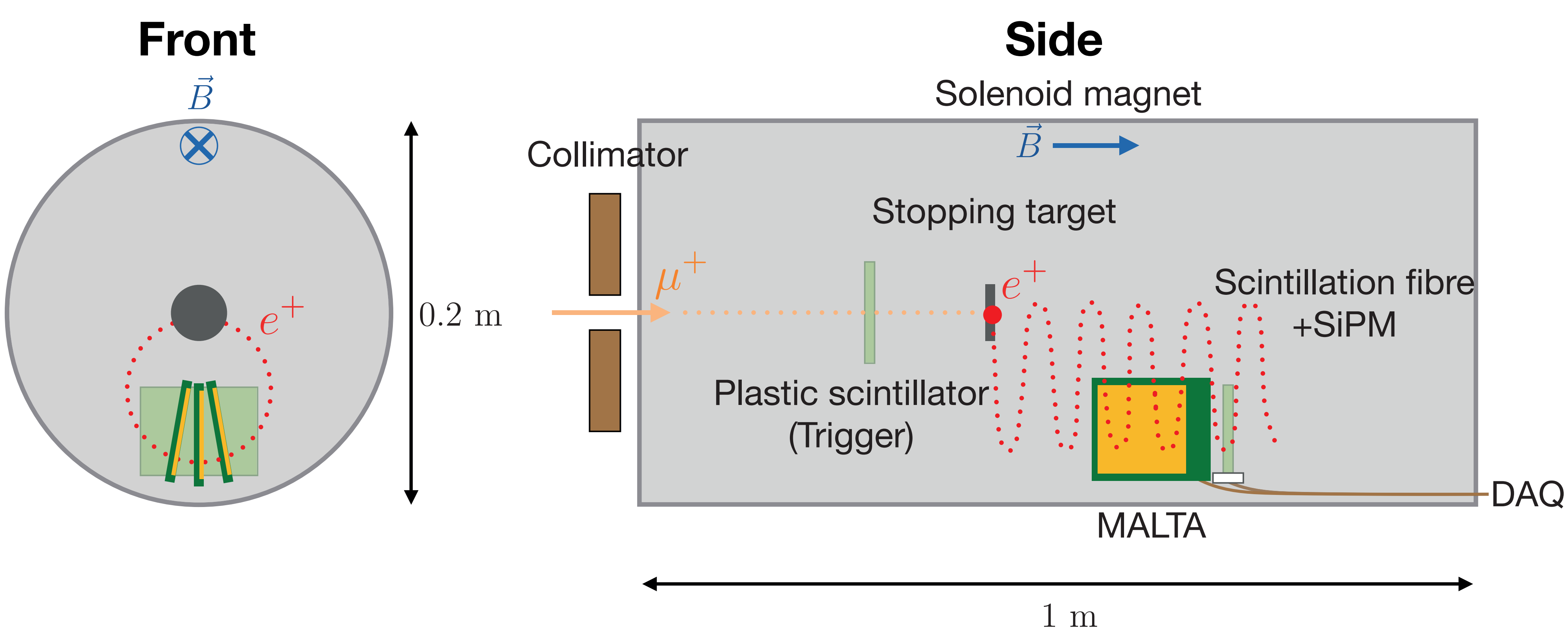



- Motivation: Establish a novel positron tracking scheme
- MALTA CMOS pixel detector is being studied
  - MAPS designed in TowerJazz 180 nm technology
  - Matrix of 512 × 512 pixels
    Pixels of 36.4 × 36.4 $\mu m^2$
  - Active area of 18.3 × 18.3 $mm^2$
- Characterisation of the MALTA is about to start!

# R&D towards muon EDM search: Next steps



- December test beam time at PSI πE1 beam line
  - Measure ~10% energy range of Michel spectrum with first MALTA tracker
  - Beam characterisation



# Summary



- The first dedicated muon EDM search at PSI is a unique opportunity which could improve the sensitivity by 4 orders of magnitude
- Characterisation of μE1 beam line was performed and data analysis is ongoing
- Detectors are being prepared for the December beam time using MALTA CMOS pixel detector

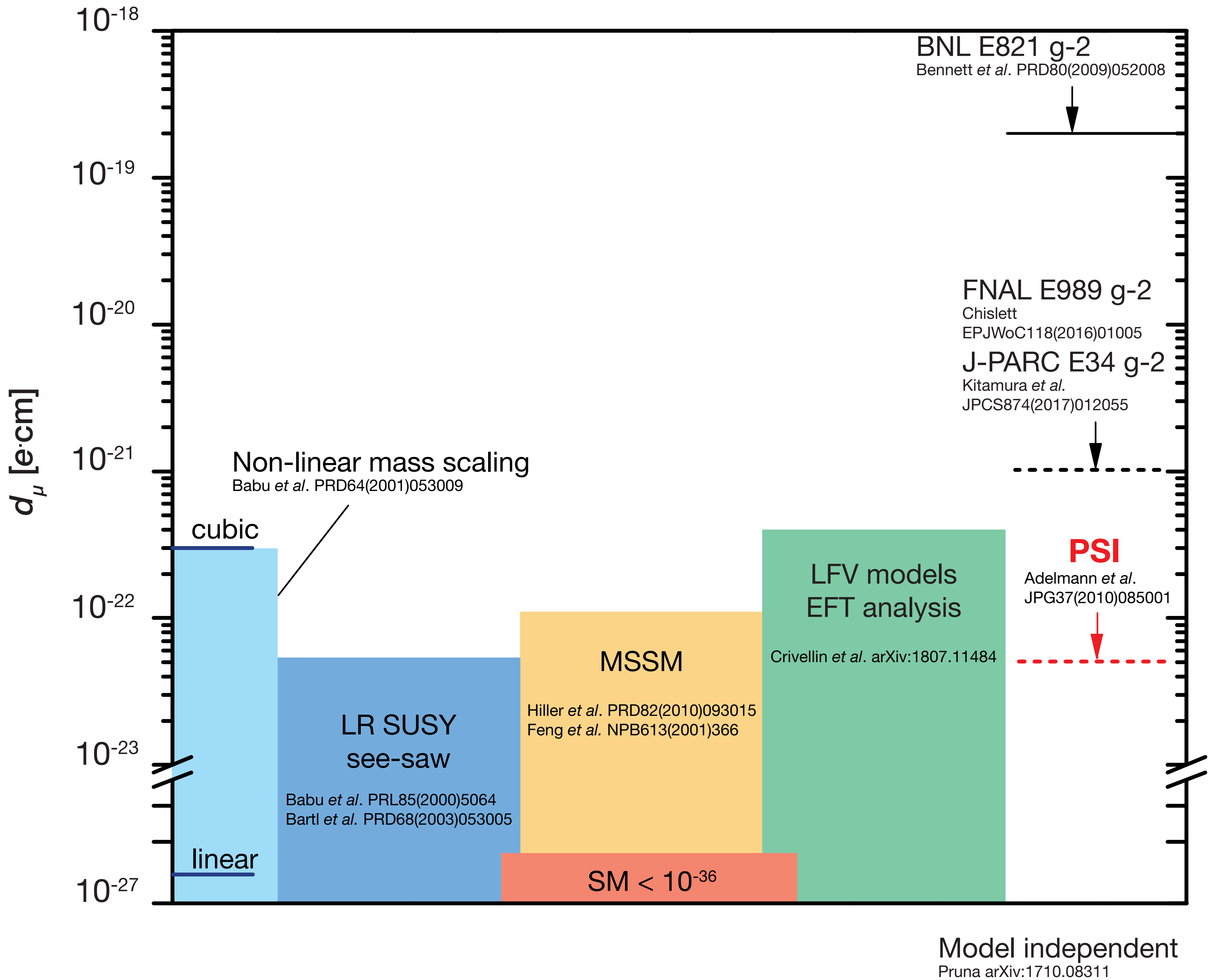
This work is supported by ETH Research Grant ETH-48 18-1



# Backups

# Muon EDM limits





# Quadrupole scan



The propagation of the beam matrix $\sigma$ is given by:

$$\sigma\left(s\right) = R \cdot \sigma\left(0\right) R^T \tag{2.19}$$

with R being in this particular example the transport matrix of the quadrupole.

$$\begin{pmatrix} \cos\left(\sqrt{K}s\right) & \frac{1}{\sqrt{K}}\sin\left(\sqrt{K}s\right) & 0 & 0 & 0 & 0 \\ -\sqrt{K}\sin\left(\sqrt{K}s\right) & \cos\left(\sqrt{K}s\right) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cosh\left(\sqrt{K}s\right) & \frac{1}{\sqrt{K}}\sinh\left(\sqrt{K}s\right) & 0 & 0 \\ 0 & 0 & \sqrt{K}\sinh\left(\sqrt{K}s\right) & \cosh\left(\sqrt{K}s\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{s}{\gamma^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{2.15}$$

- Multiplication of transport matrices for successive passive through elements and free space