PAUL SCHERRER INSTITUT

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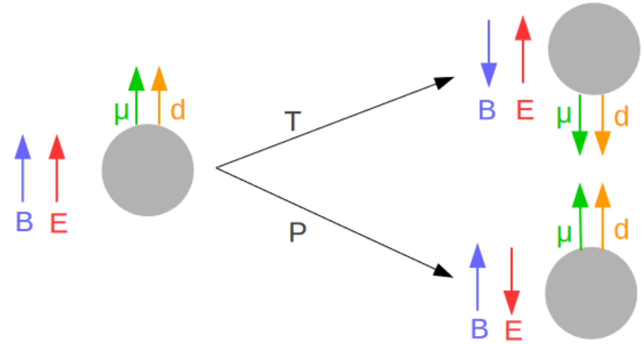
Search for a muon electric dipole moment using the frozen-spin technique

Ljiljana Morvaj (PSI), on behalf of the *muEDM@PSI* collaboration

Motivation

- Interaction of a particle spin with EM fields: $\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$
  - ➢Magnetic & electric dipole moment (EDM) ⟶ $\vec{\mu} = g\frac{e}{2m}\vec{s}$ $\vec{d} = \eta\frac{q}{2m}\vec{s}$

- **EDM violates parity (P) & time-reversal (T)**
  - ➢Under the assumption of CPT => CP violation
  - ➢Need BSM CP-violating sources to explain the **baryon asymmetry in the Universe**



- Muon EDM SM value is many orders of magnitude below current experimental sensitivities
  - ➢ **Observation of EDM → new physics!**

Current status of muon EDM

Indirect limit assuming MFV derived by scaling electron EDM: $|d_\mu^{\mathrm{MFV}}| < 2.3 \times 10^{-27}\ e\,\mathrm{cm}$

- **But MFV strongly challenged by $g-2$ & B-decay anomalies!**

Best direct limit (PhysRevD.80.052008):

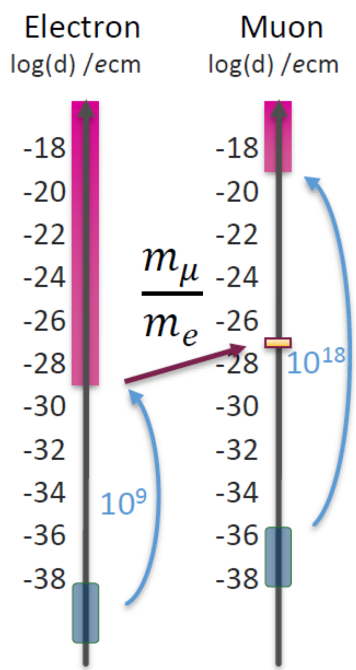
$$d_\mu \le 1.8{\times}10^{-19}\ e{\cdot}\mathrm{cm}$$

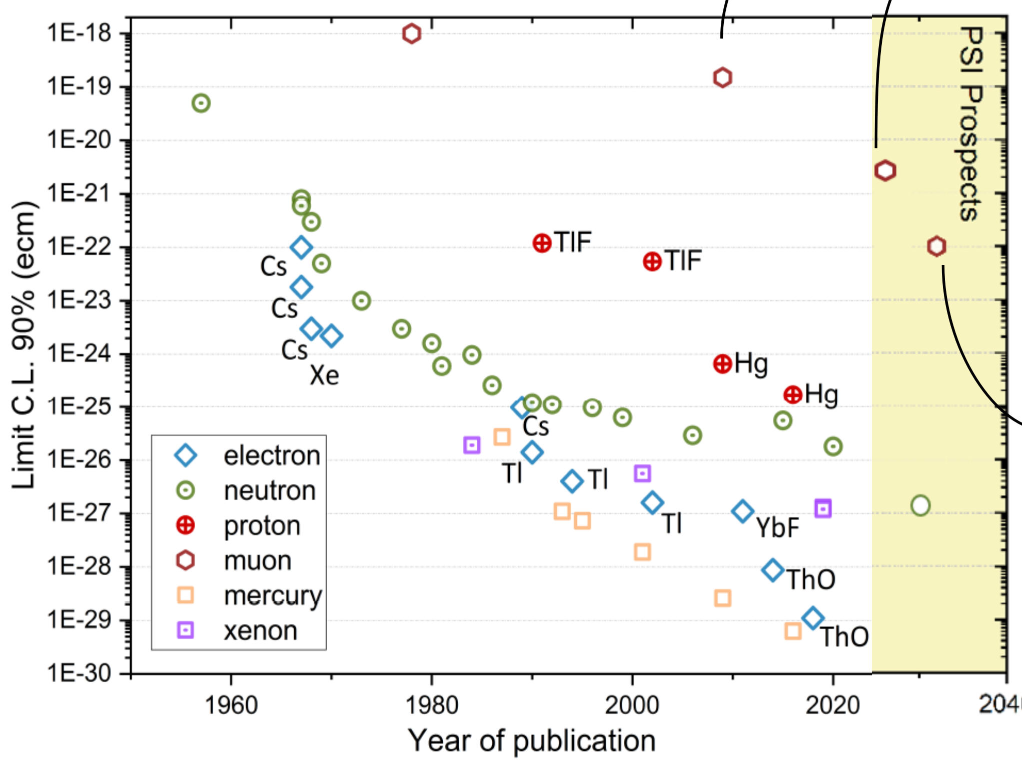
PSI (Phase I):

$$<3 \times 10^{-21}\ e{\cdot}\mathrm{cm}$$

PSI (Phase II):

$$< 6 \times 10^{-23}\ e{\cdot}\mathrm{cm}$$





Measurement principle

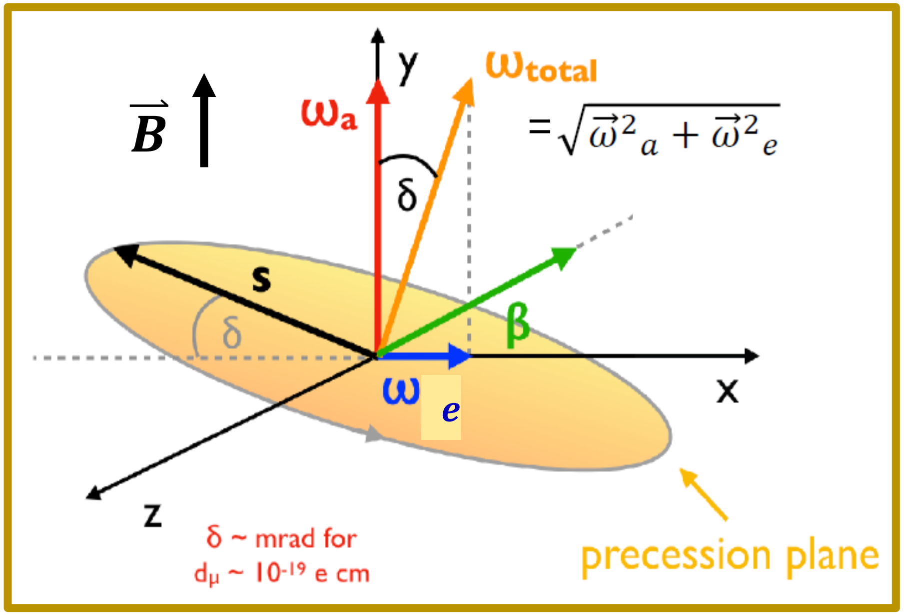
- Muon spin precesses in the presence of $\vec{E}$ & $\vec{B}$ fields
  - **Measure the precession frequency/plane** (knowing the fields)
    - → **infer a_u & d_u**

$$\vec{\omega} = \vec{\omega_a} + \vec{\omega_e} = -\frac{e}{m_\mu}\left[\left\{a_\mu \vec{B} - \left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right\} + \frac{\eta}{2}\left\{\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right\}\right]$$

$g-2$ term (a_μ) → spin precession in the plane of motion

EDM term (d_μ) → spin precession orthogonal to the plane of motion

$(\vec{E} \perp \vec{B} \perp \vec{\beta})$



Simplifying the measurement

- **BNL/FNAL**
  - ➢"Magic" momentum: 3.09 GeV

$$\vec{\omega} = -\frac{e}{m_\mu}\left[\left\{a_\mu \vec{B} - \left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right\} + \frac{\eta}{2}\left\{\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right\}\right]$$

- **J-PARC**
  - ➢No *E* field for focusing

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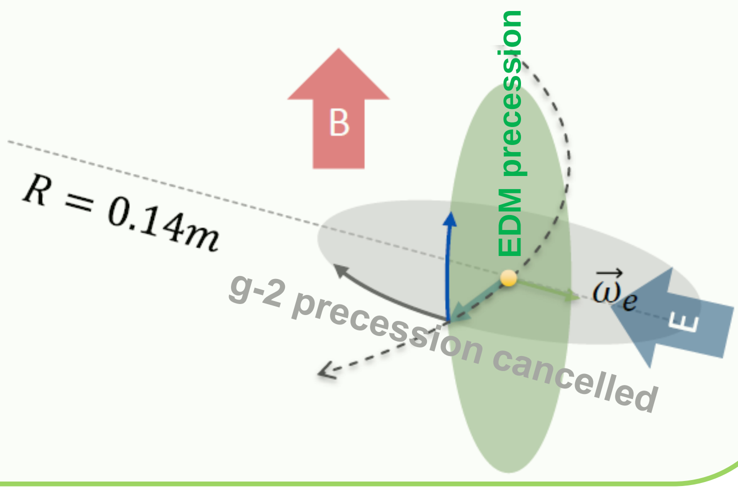
- **PSI: The frozen spin technique**

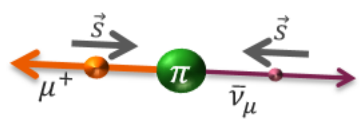
$$\vec{\omega} = -\frac{e}{m_\mu}\left[\left\{a_\mu \vec{B} - \cancel{\left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right\} + \frac{\eta}{2}\left\{\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right\}\right]$$

  - ➢Apply radial *E* field such that it cancels the $g-2$ term
    - ▪ No EDM:
      - – spin frozen to the direction of motion
    - ▪ EDM:
      - – Spin precession only in the plane orthogonal to the plane of motion

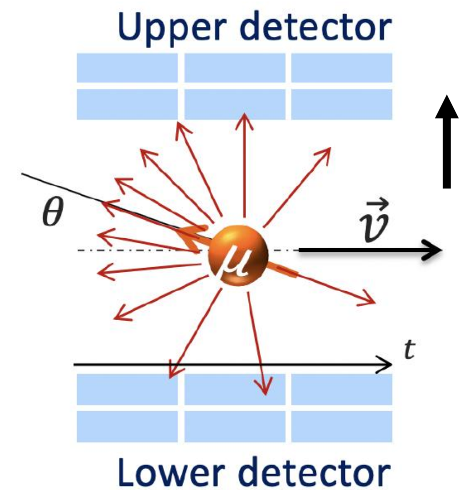


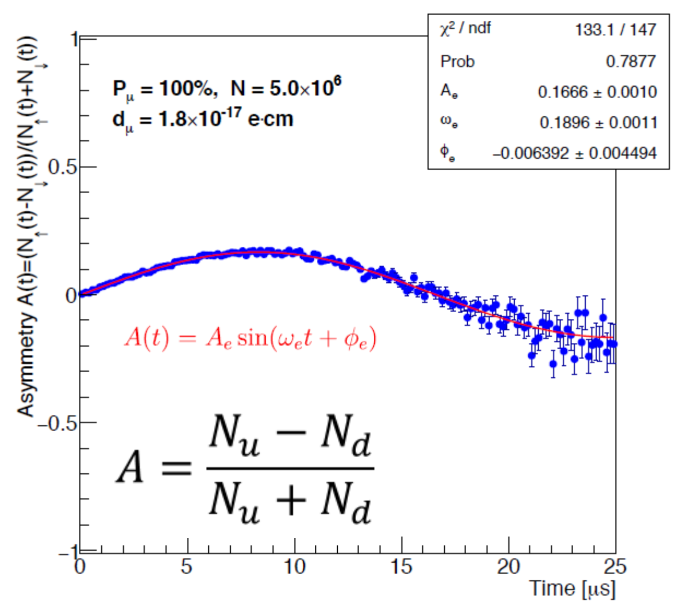
Detection technique

- **Polarized (~95%) μ^+** produced in pion decays



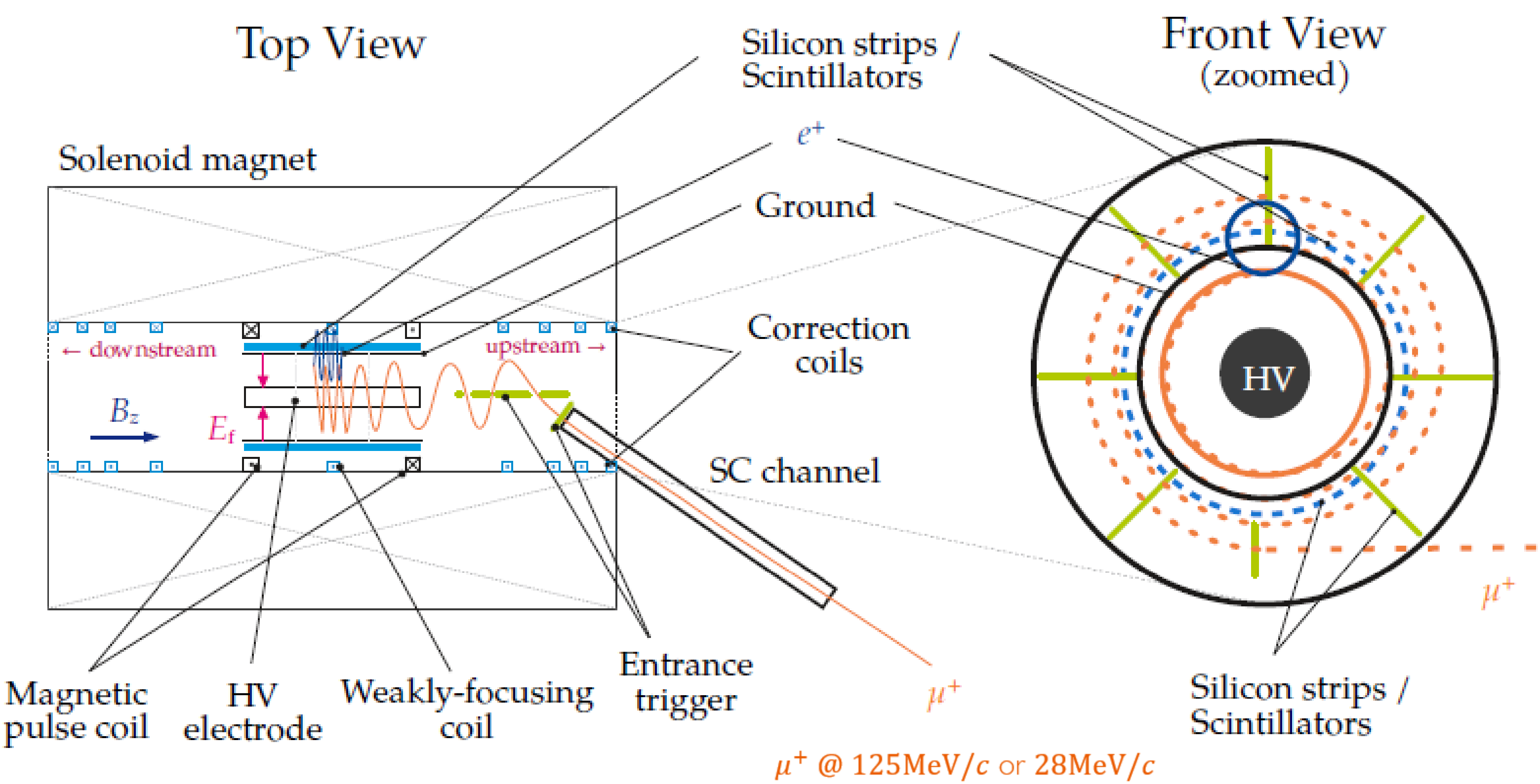
- Decay e^+ emitted preferentially in the spin direction
- Count the number of e^+ in the "up" and "down" detectors
- In the **absence of EDM** the spin is frozen along momentum direction
  - ➢ **no asymmetry**
- **Non-0 EDM**:
  - ➢ spin precession out of the orbit plane
  - ➢ **build up of the "up-down" asymmetry with time**





Experiment layout

- Muons injected through a superconducting (SC) channel
- Fast entrance scintillator triggers magnetic pulse that stops the longitudinal μ^+ motion
- Weakly focusing field for storage
- Thin electrodes provide an electric field (*3 kV/cm*) for the frozen spin
- Si strip/scintillator detectors for decay e+ tracking



Phased approach

Phase I

- **p=28 MeV** muons
- Existing solenoid at PSI, max 5 T
- Bore diameter 200 mm
- Length 1 m
- Field measured in 2022 & found suitable for injection

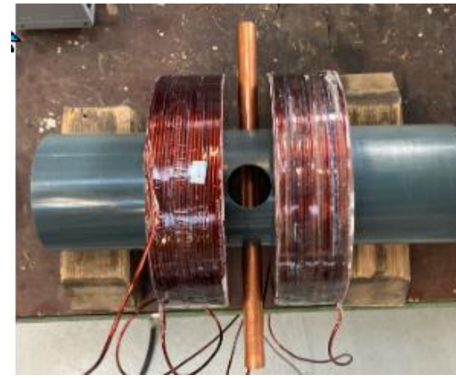
Phase II

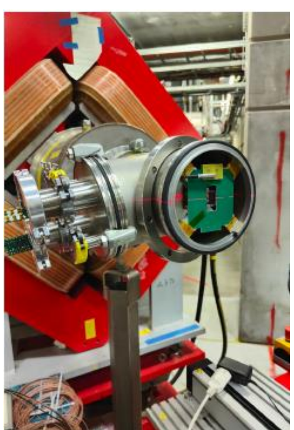
- **p=125 MeV** muons
- Larger bore (up to 900 mm diameter)
- Better spatial and temporal stability

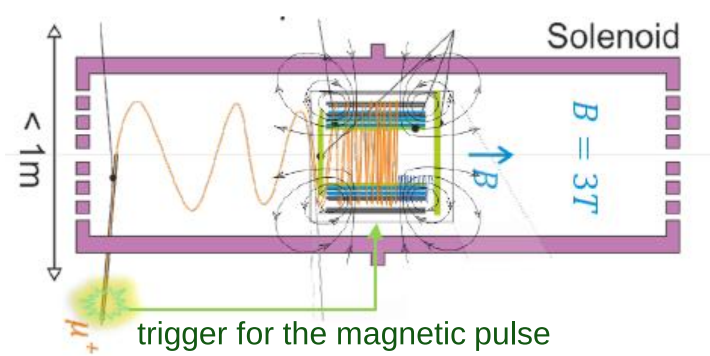
	Phase I	Phase II
	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.017	0.60
Muon storage rate (1/s)	2×10^3	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	500	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.3	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year (e·cm)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

Muon injection and entrance trigger

- **Superconducting injection tube**
  - ➢Transport muons in a magnetic field-free region into the strong B of the storage solenoid (without them spiraling out due to the Magnetic Mirror Effect)
  - ➢Testing different materials







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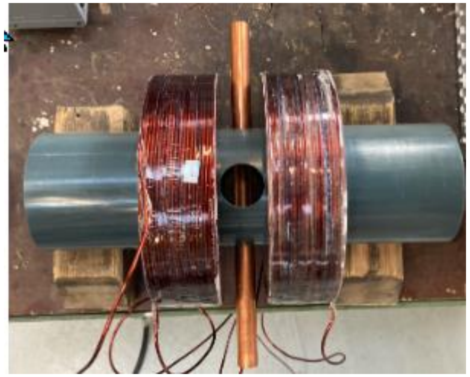
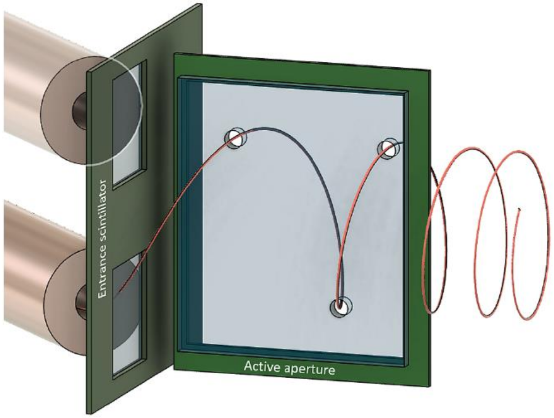
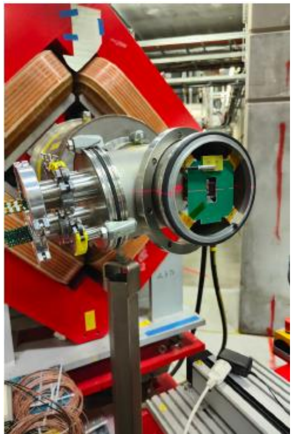
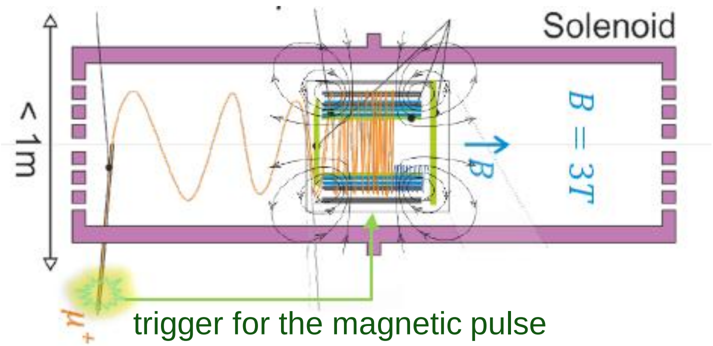


- **Entrance detector: thin scintillator (100 um) + active aperture**
  - ➢ Minimize multiple scattering for the muons within the acceptance phase space
  - ➢ Generate trigger signal for the magnetic kick







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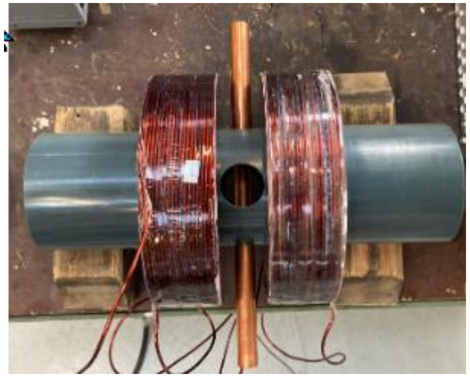

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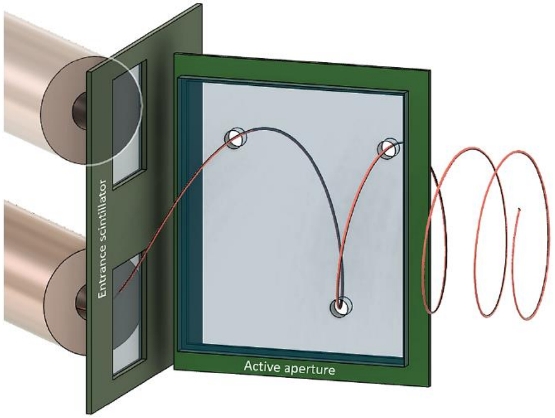
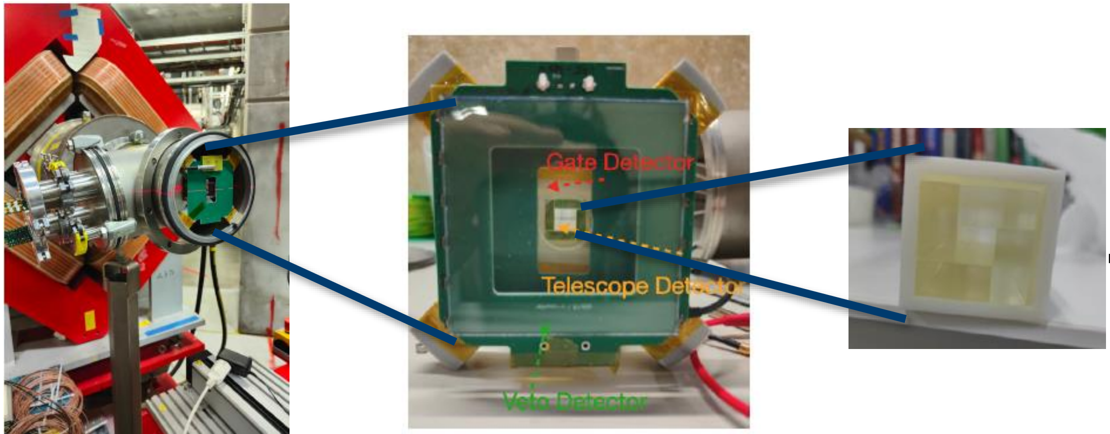
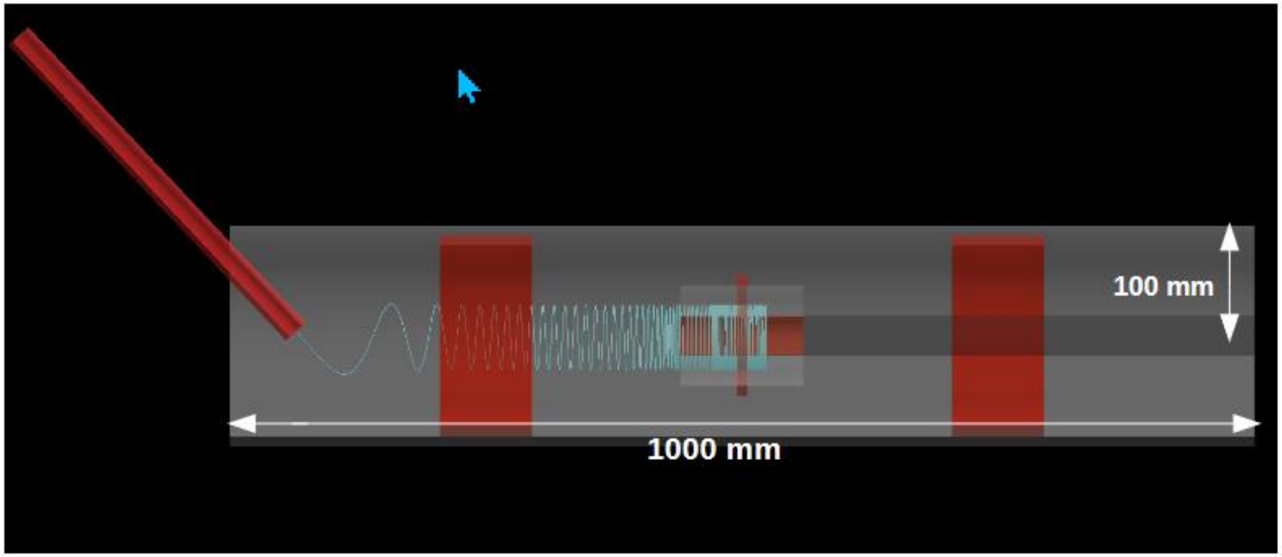




- **Beam test 2022:**
  - ➢Demonstrated feasibility of anti-coincidence triggering

Muon trajectory simulations

- Running G4Beamline simulations to determine the best parameters for the muon injection

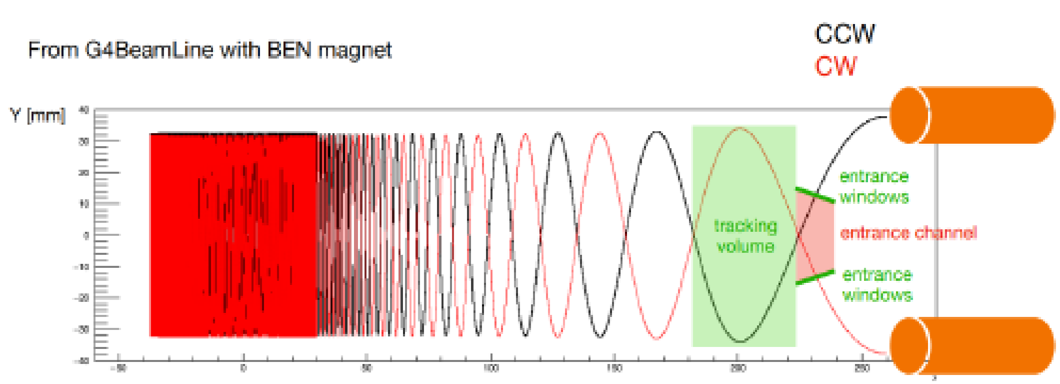


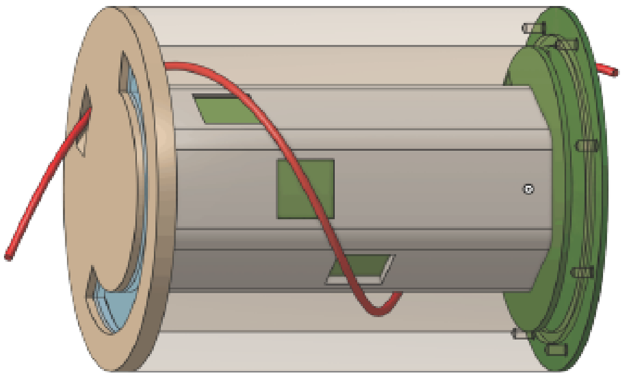
- Best guess initial parameters:
  Injection angle, $\theta = 47.42^0$
  Initial injection radius, r = 40.19 mm
  Longitudinal injection coordinate, z = 435 mm
  Initial angle on transverse plane, $\varphi = 5.65^0$

- Muons can be stopped with a peak time of ~ 140 ns

Muon tracking

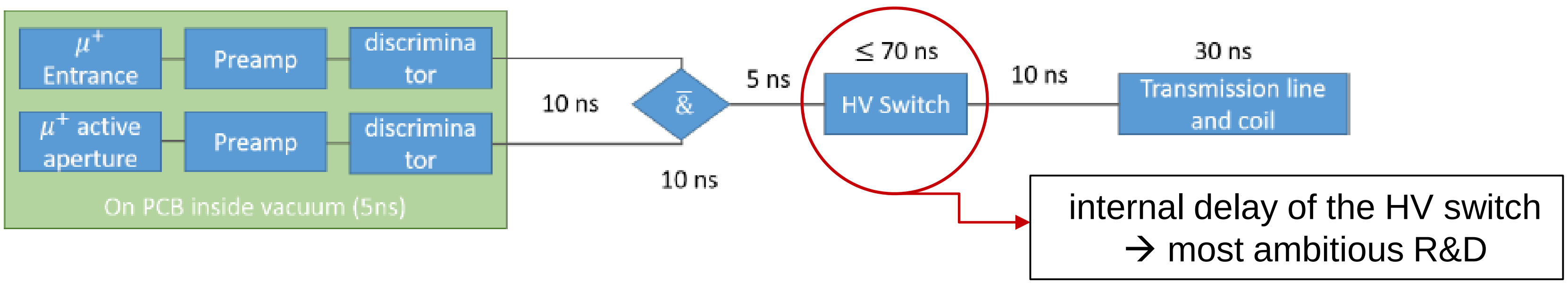
- **Characterize muon trajectory before EDM measurement**
  - ➢Measure the injection angle (~mrad) and momentum (~1%)
  - ➢Stability of injected muon trajectories important for high trapping efficiency, precise triggering and cancelation of systematic uncertainties between clockwise (CW) & counter-clockwise (CCW) injections
- **Gaseous TPC chamber with GridPix readout**
  - ➢Need a very light/low pressure gas mixture and a very thin entrance window to minimize MS
  - ➢Tracking over ~1 full turn of the muon

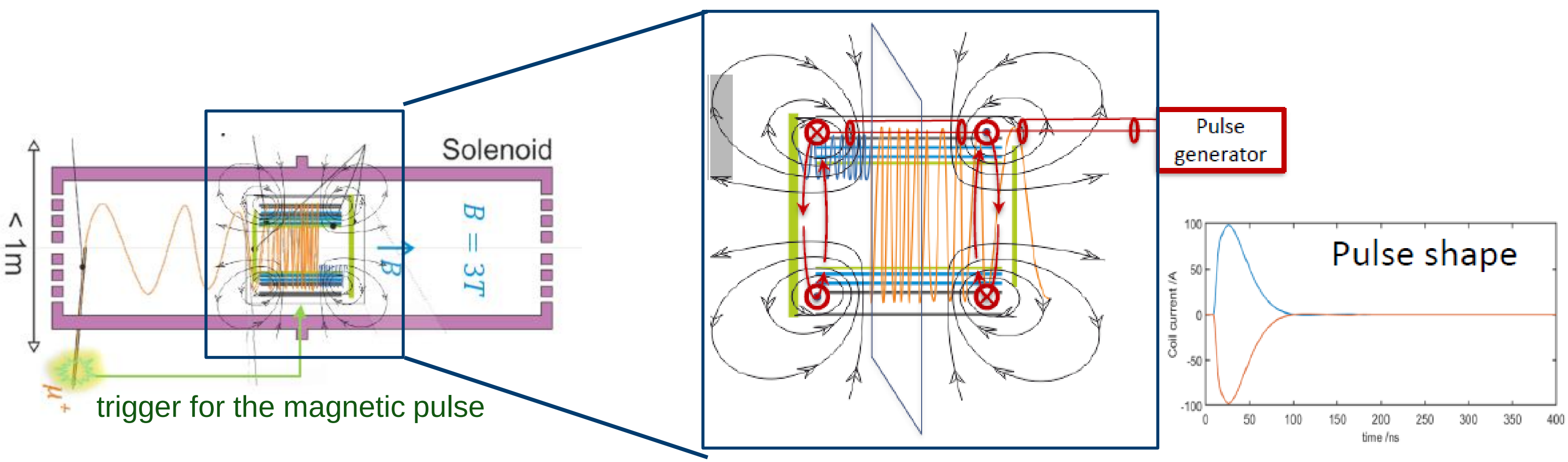




Magnetic pulse

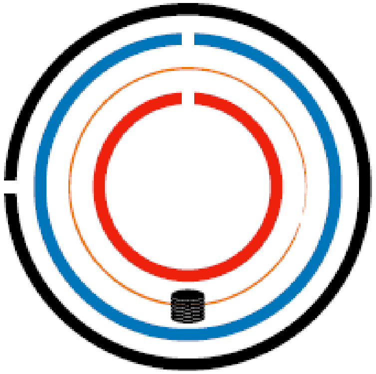
- **Quadrupole field pulse to cancel the longitudinal muon momentum**
- Delay between the trigger and the pulse needs to be $\leq 150\ ns$





Magnetic pulse & electrodes

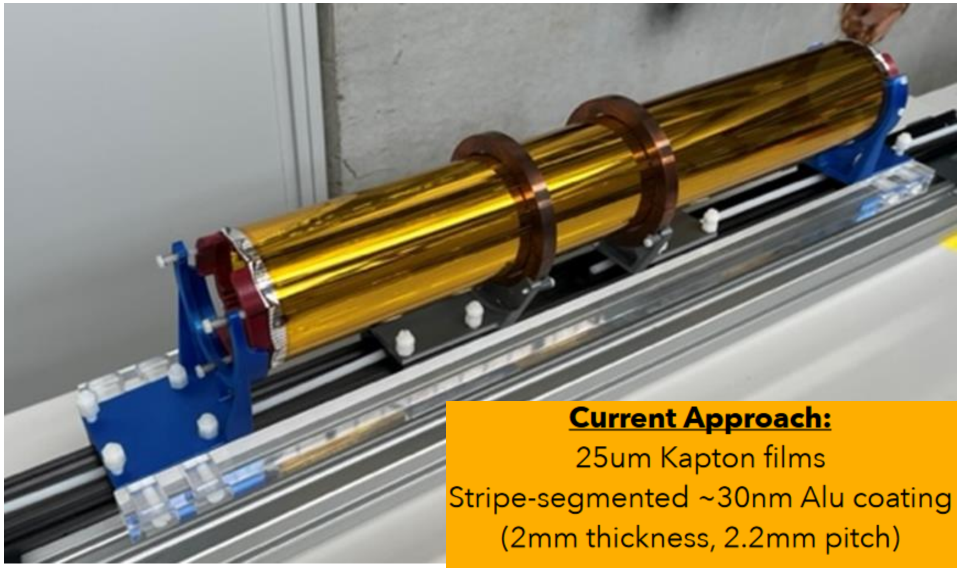
- **Shielding** of the magnetic pulse seen by the muon due to the **eddy currents induced in the frozen-spin electrodes**
  - ➢ Factor ~3 shielding measured with uniform Alu coated electrodes
  - ➢ **Close to no shielding with stripe-segmented Alu coating!**



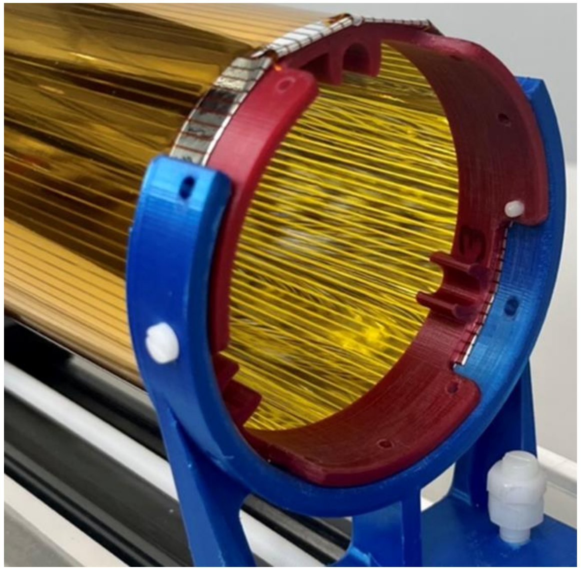
PulseCoil : Alu, $10 \times 10\text{mm}^2$, IR = 40 mm

GND : Alu/Kapton 30 nm

+HV : Alu/Kapton 30 nm



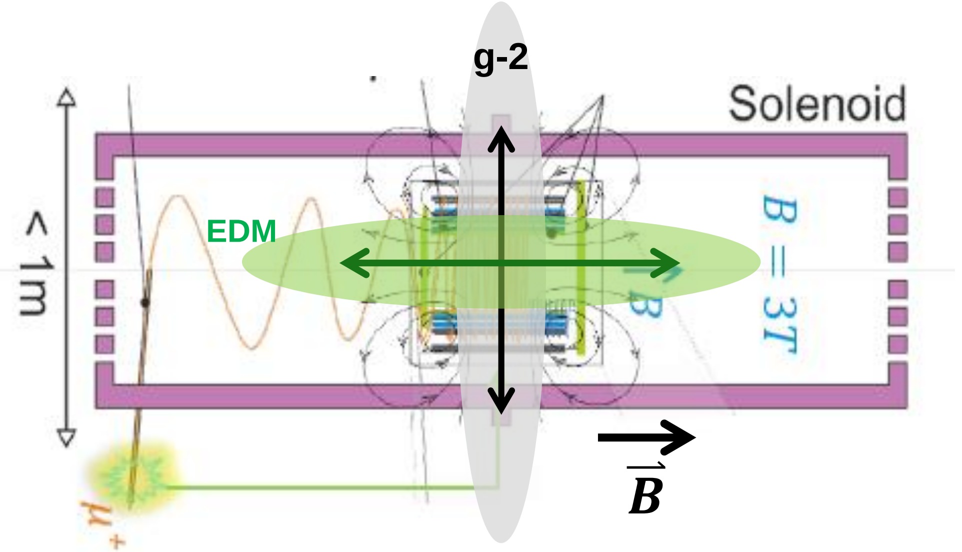
Current Approach:
25um Kapton films
Stripe-segmented ~30nm Alu coating
(2mm thickness, 2.2mm pitch)



Asymmetry measurements

- **Detection of g-2 precession**
  a) **Measure <B> field** seen by muons in the storage zone
  b) **Tune the radial E field to the frozen spin condition**

- **Detection of EDM precession**
  - Measurement of the **longitudinal** (along the *B* field) **asymmetry** as a function of time: A(t)



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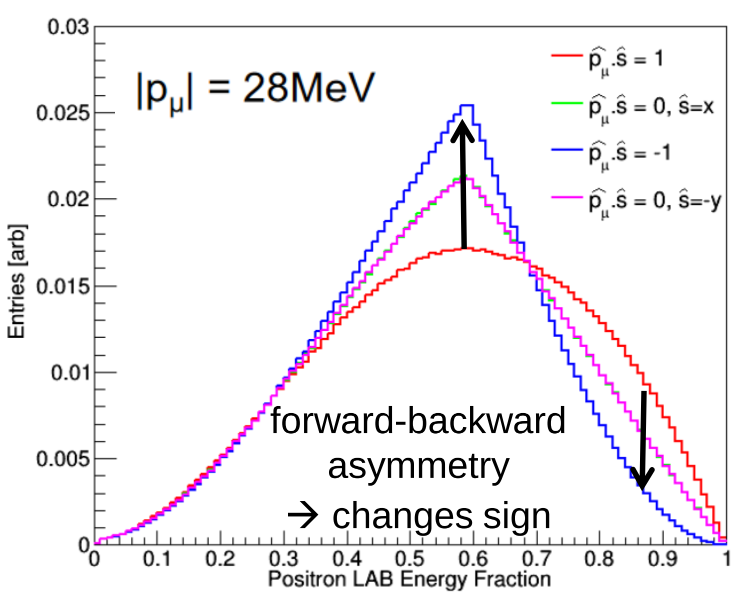
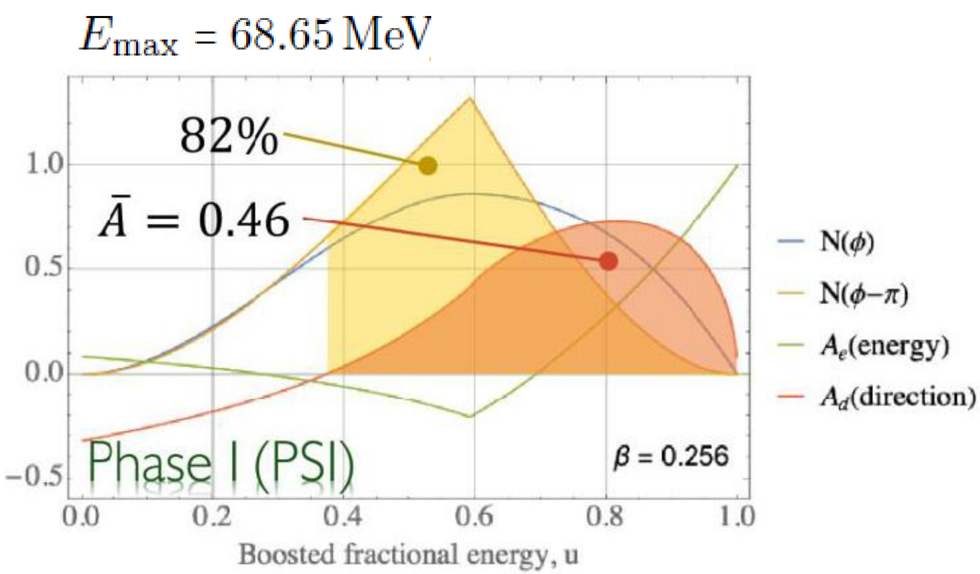
  - ➢ Requires momentum resolution (~MeV)

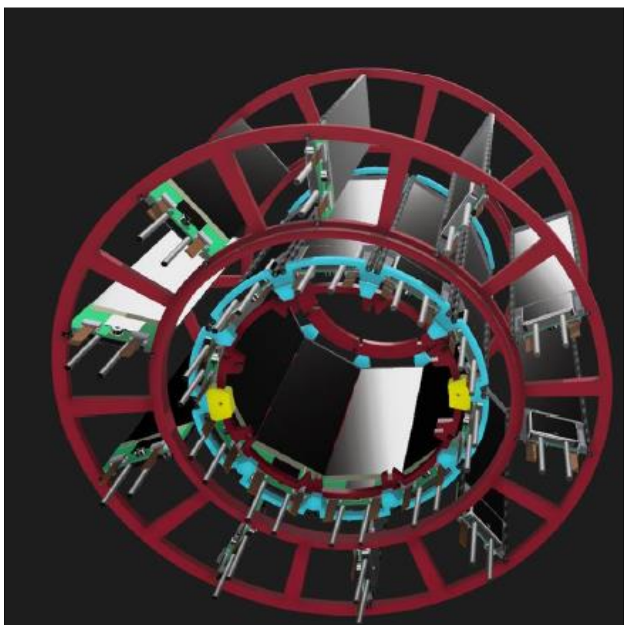
- **Detection of EDM precession**
  - ➢ Measurement of the **longitudinal** (along the *B* field) **asymmetry** as a function of time: A(t)
  - ➢ Requires spatial resolution along the cylinder (~mm)

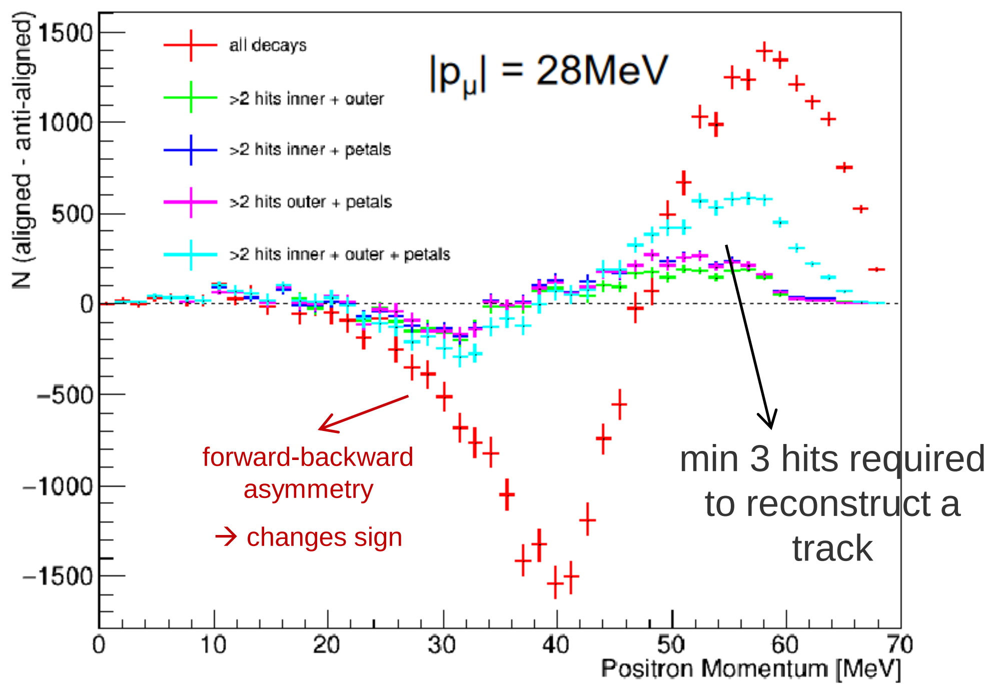




Positron detection for g-2

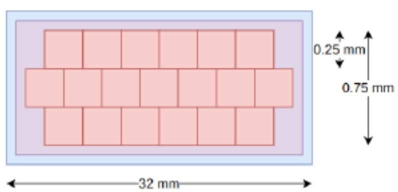
- **Si strip detector for forward-backward asymmetry measurement**
  - ➢ 2 cylindrical layers (r=35 mm, 47.5 mm) + petals
  - ➢ optimizing detector geometry and layout to maximize momentum acceptance and track reconstruction efficiency, with as low material budget as possible

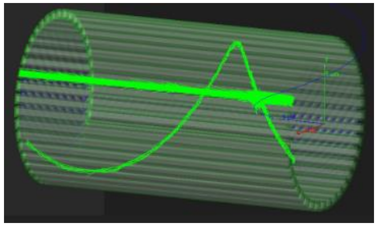


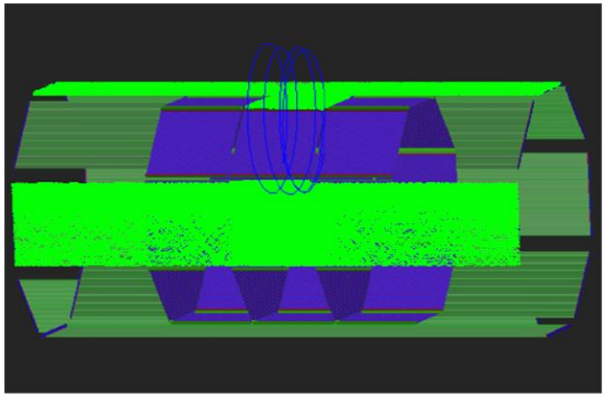


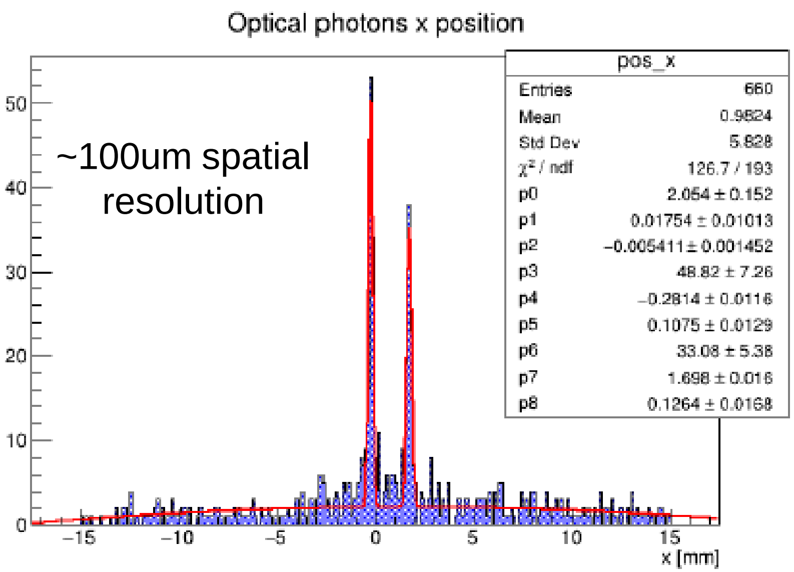
Positron detection for EDM signal

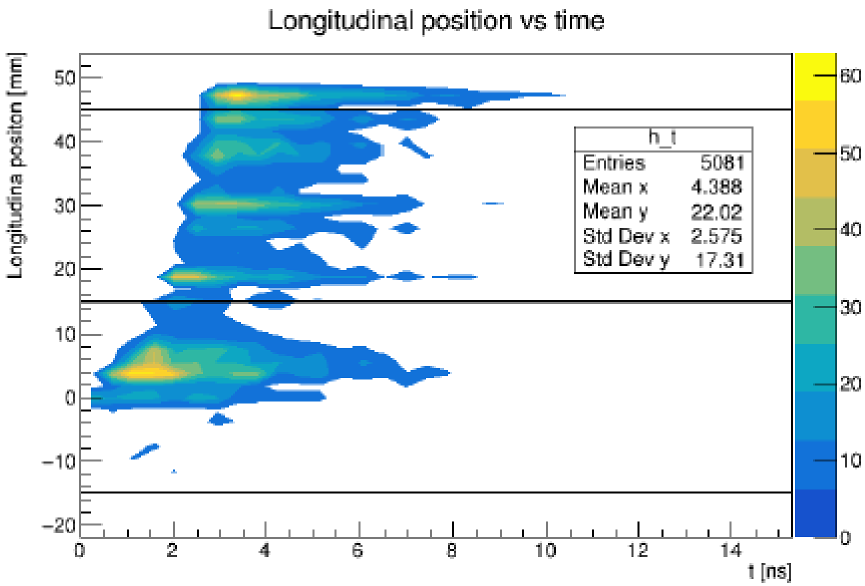
- **Scintillating fibers** (250 um) with transverse and longitudinal segmentation
  - ➢ **Measure longitudinal EDM asymmetry**
  - ➢ Reconstruction of (longitudinal) momentum
  - ➢ Timing resolution of a single fiber <2 ns











Systematic effects

- All effects that lead to a ***real*** or ***apparent*** spin precession around the radial axis that are not related to the EDM
  - Coupling of a_μ with the EM fields of the experimental setup ***(real)***
  - Early to late variation of detection efficiency of the EDM detectors (***apparent***)

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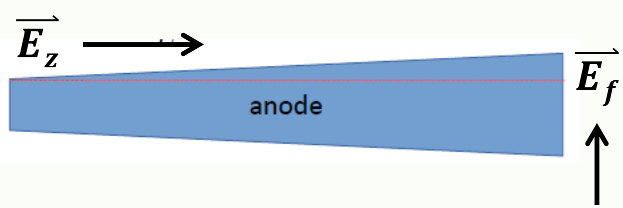
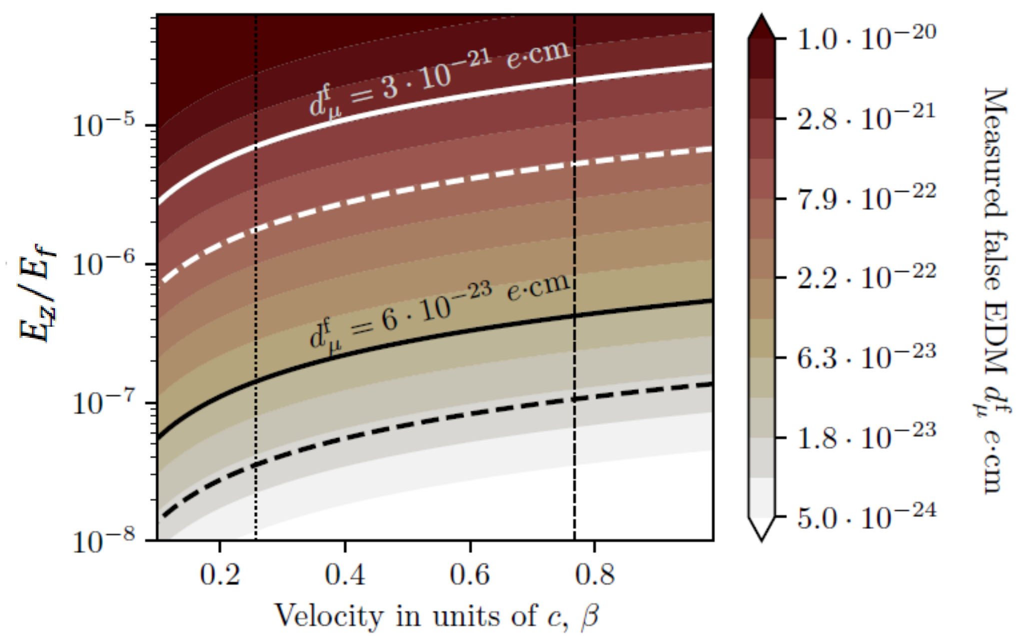
- Example:
  - ➢ Non-constant radius of cylindrical anode → induces E_z
    - ▪ syst proportional to $\vec{\beta} \times \vec{E}$





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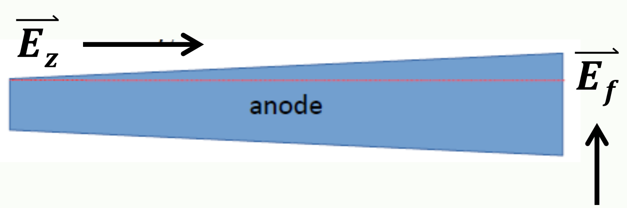
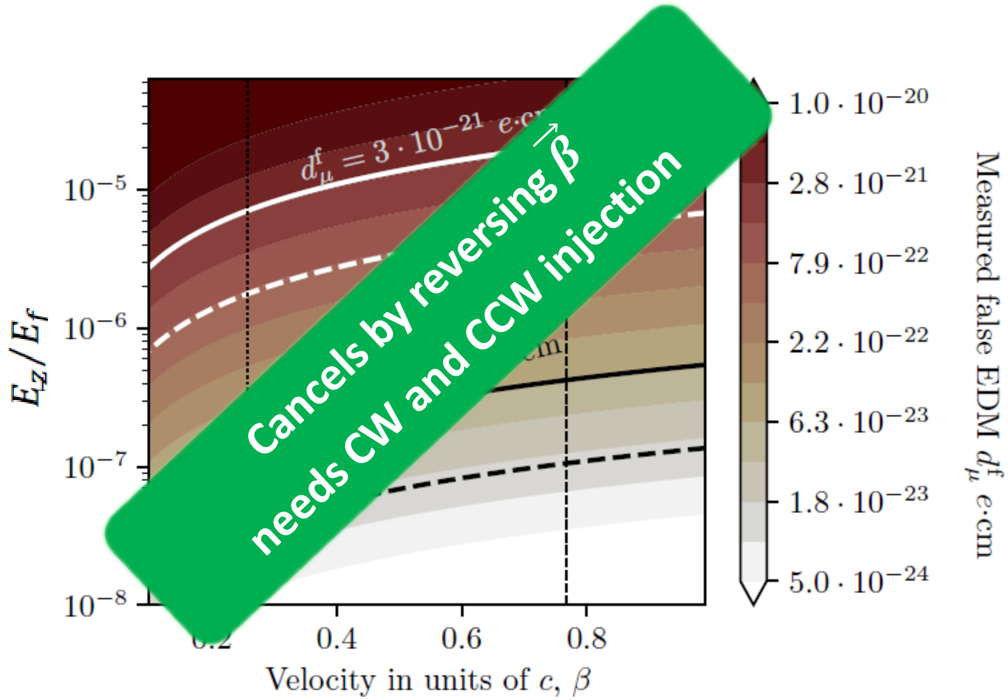
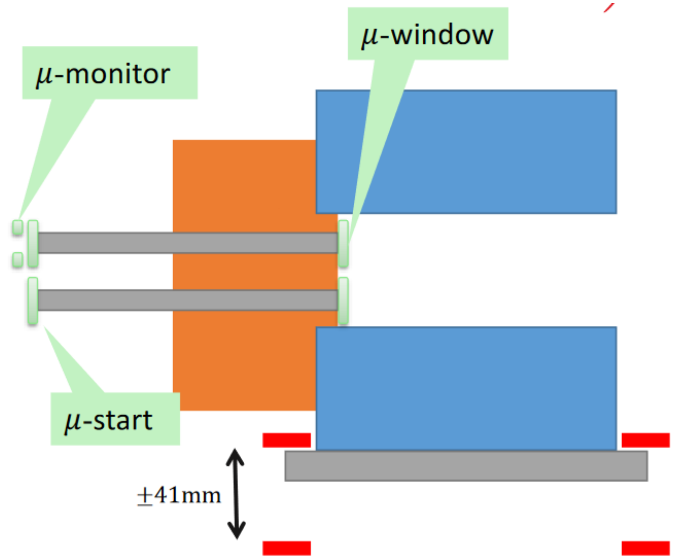


- **➢Cancel by reversing $\vec{\beta}$ (& $\vec{B}$)!**
  - ▪ EDM signal: $\vec{\beta} \times \vec{B}$



Phase I commissioning plans

- Beam time 2023:
  - Align the experiment to the beam using a prototype of a segmented scintillating beam monitor
  - Measure the ToF stability between CW & CCW injections
    - with and without B field
    - need Δp<0.5% to cancel out syst



- 2024
  - Injection through the SC channel; stop the muons in a target and measure the decay asymmetry
- 2025
  - Muon storage using the magnetic pulse, g-2 measurement and freezing the spin
- 2026
  - Phase I data-taking!

Summary

- **A dedicated experiment to search for a muon EDM is being set-up at PSI**
  - Optimization of the design using simulations
  - Detector prototypes
  - Test beams for demonstrating feasibility
- **Expected sensitivity 3 orders of magnitude beyond current experimental limits**
  - Phase I: $<3 \times 10^{-21}\ e\cdot\text{cm}$
  - Phase II: $< 6 \times 10^{-23}\ e\cdot\text{cm}$

The collaboration (& growing)

PSI Proposal No. R-21-02.1
Measurement of the Muon Electric Dipole Moment

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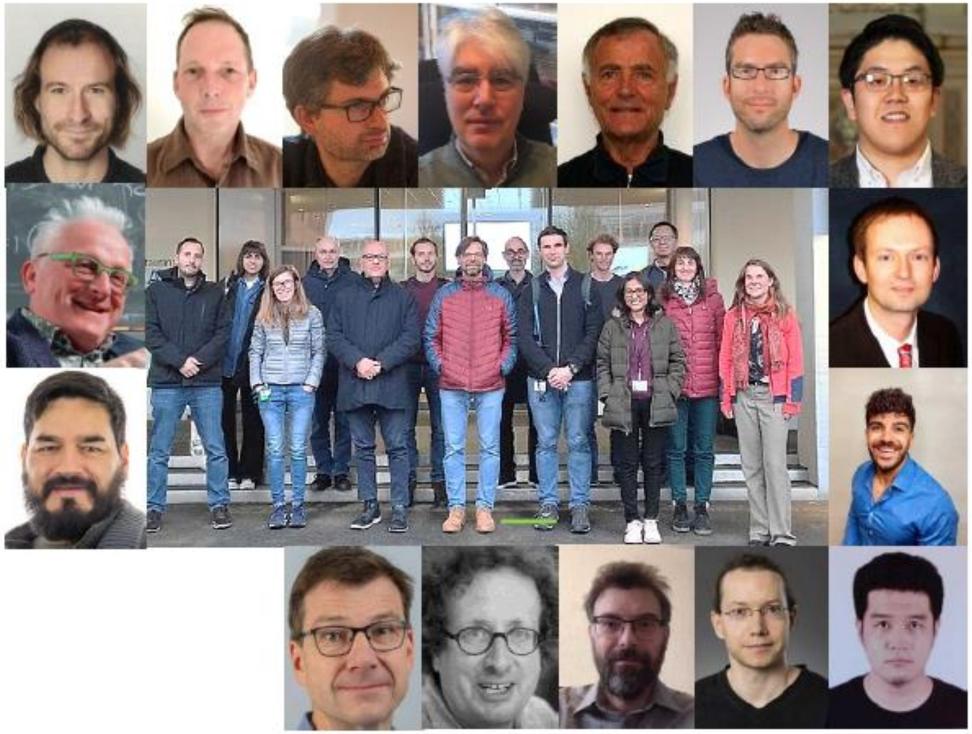
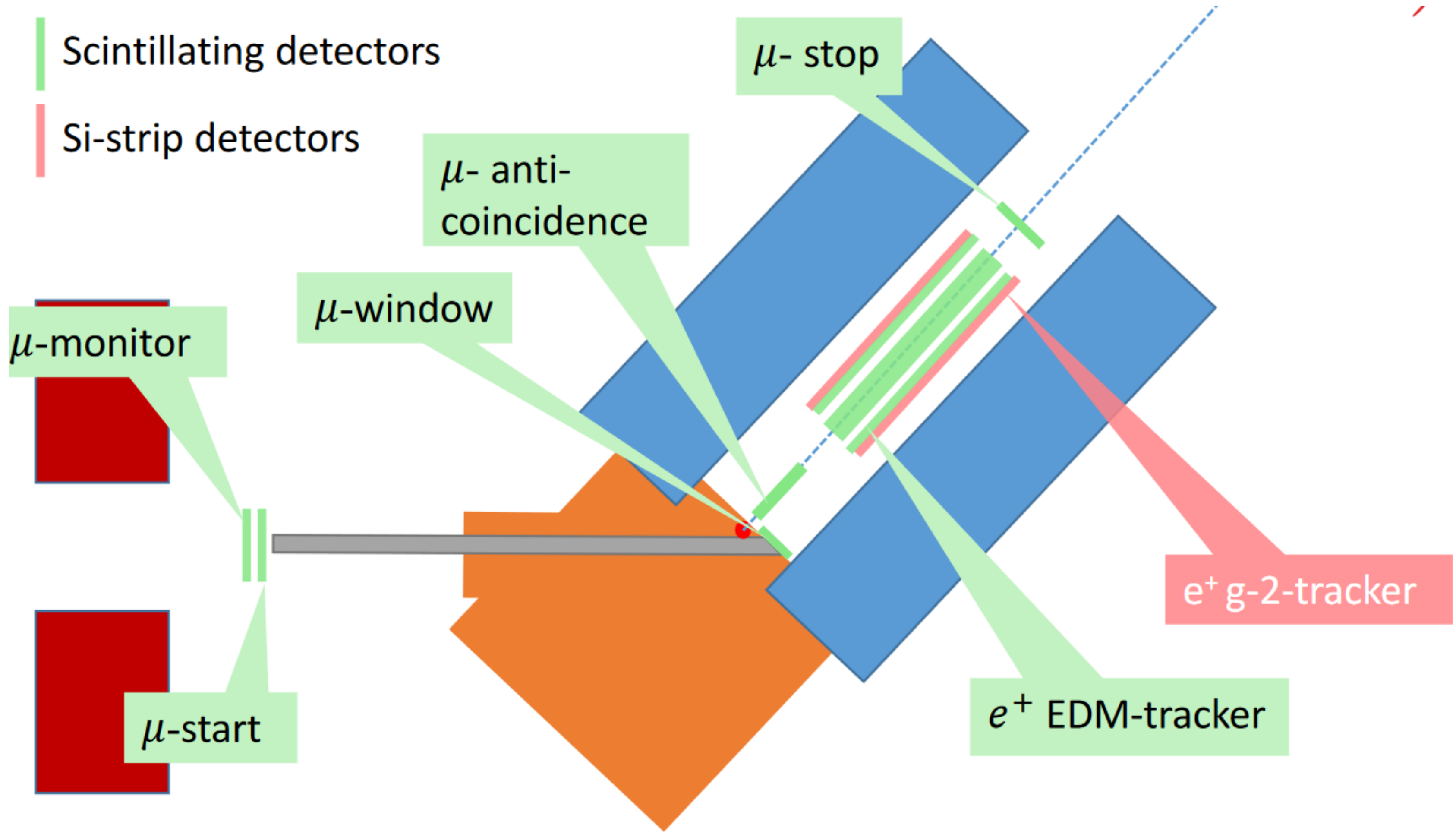


Backup



Scintillating detectors
Si-strip detectors
μ- stop
μ- anti-coincidence
μ-window
μ-monitor
μ-start
e+ g-2-tracker
e+ EDM-tracker

Statistical sensitivity

- For B = 3T, p = 28 MeV and 125 MeV : $E_\mathrm{f} = 0.3\,\mathrm{MV/m}$ and $E_\mathrm{f} = 1.9\,\mathrm{MV/m}$

$$\sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0 E_\mathrm{f}\sqrt{N}\tau_\mu A}$$

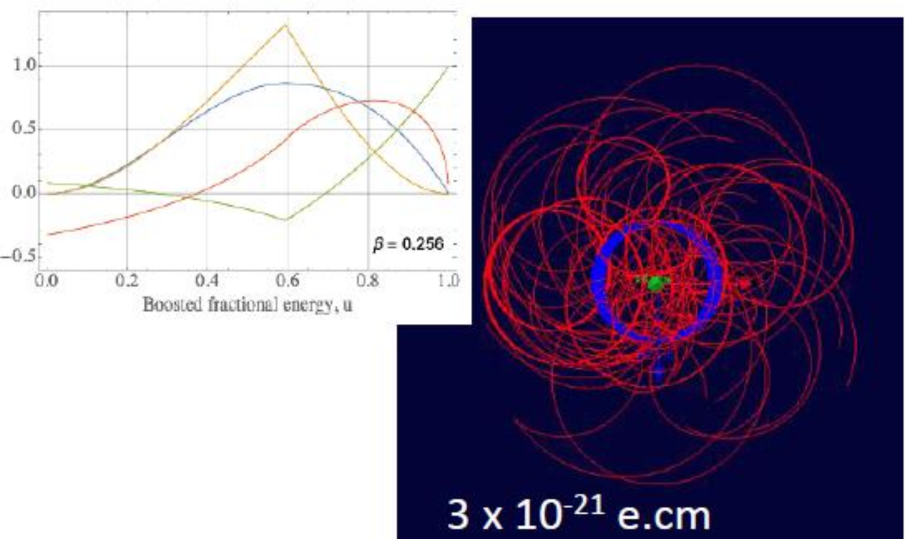
$$E_\mathrm{f} \approx aBc\beta\gamma^2$$

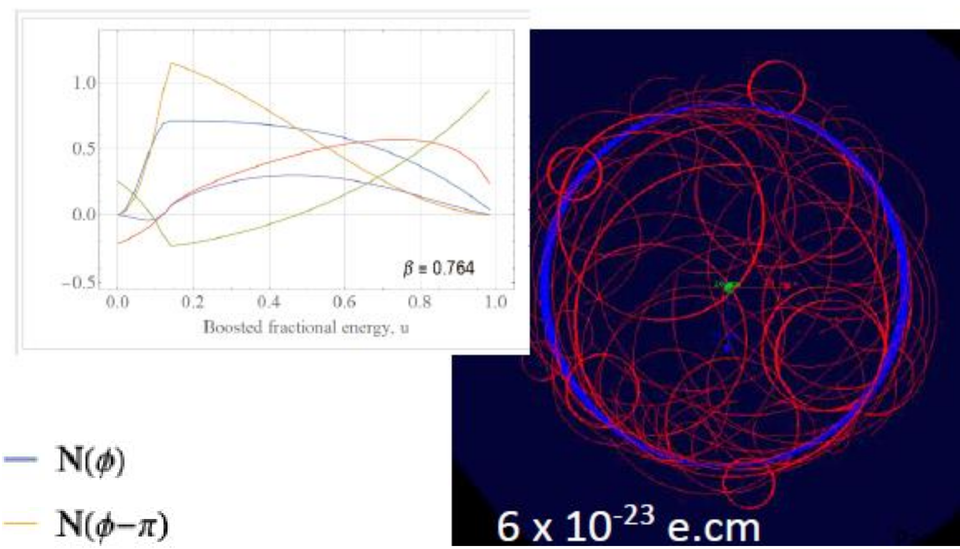
	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.017	0.60
Muon storage rate (1/s)	2×10^3	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	500	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.3	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e\cdot$cm)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

Going from Phase I to Phase II

Phase I
- B-Field 3T
- Momentum 28 MeV/c
- Muon radius 31mm
- Most positrons outside

Phase II
- B-Field 3T
- Momentum 125 MeV/c
- Muon radius 141 mm
- Most positrons inside

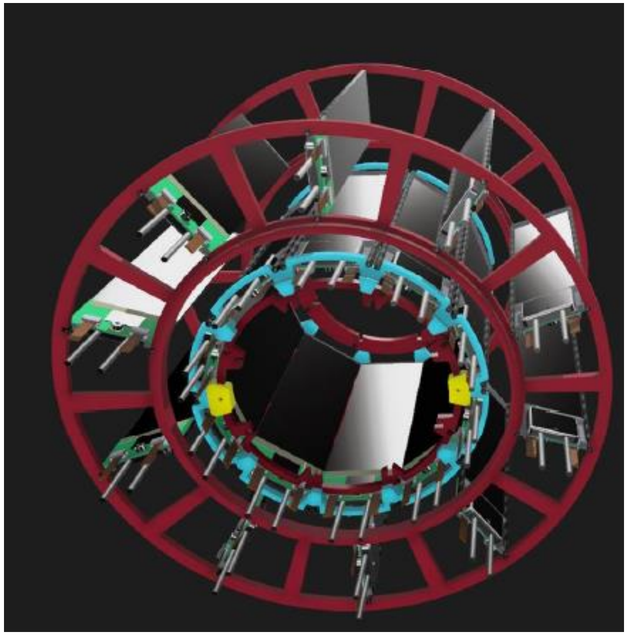


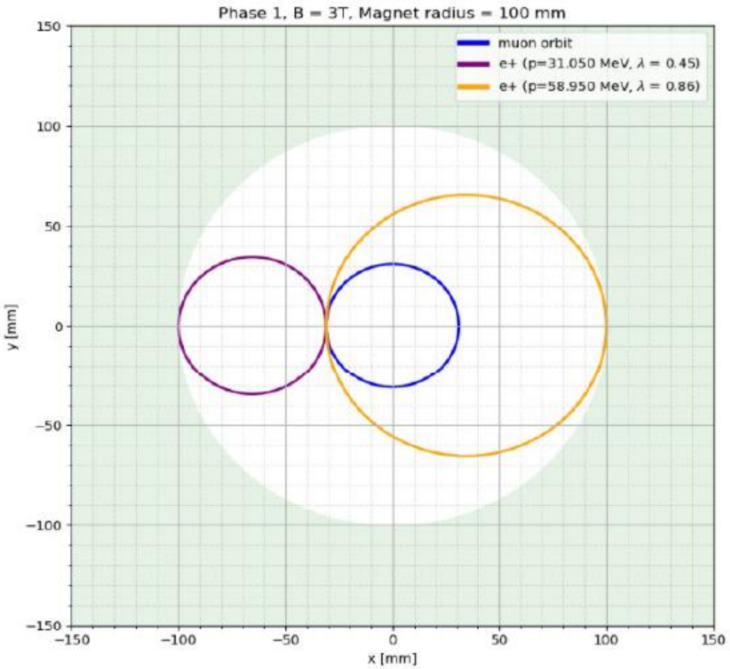


— $N(\phi)$
— $N(\phi-\pi)$
— A_e(energy)
— A_d(direction)

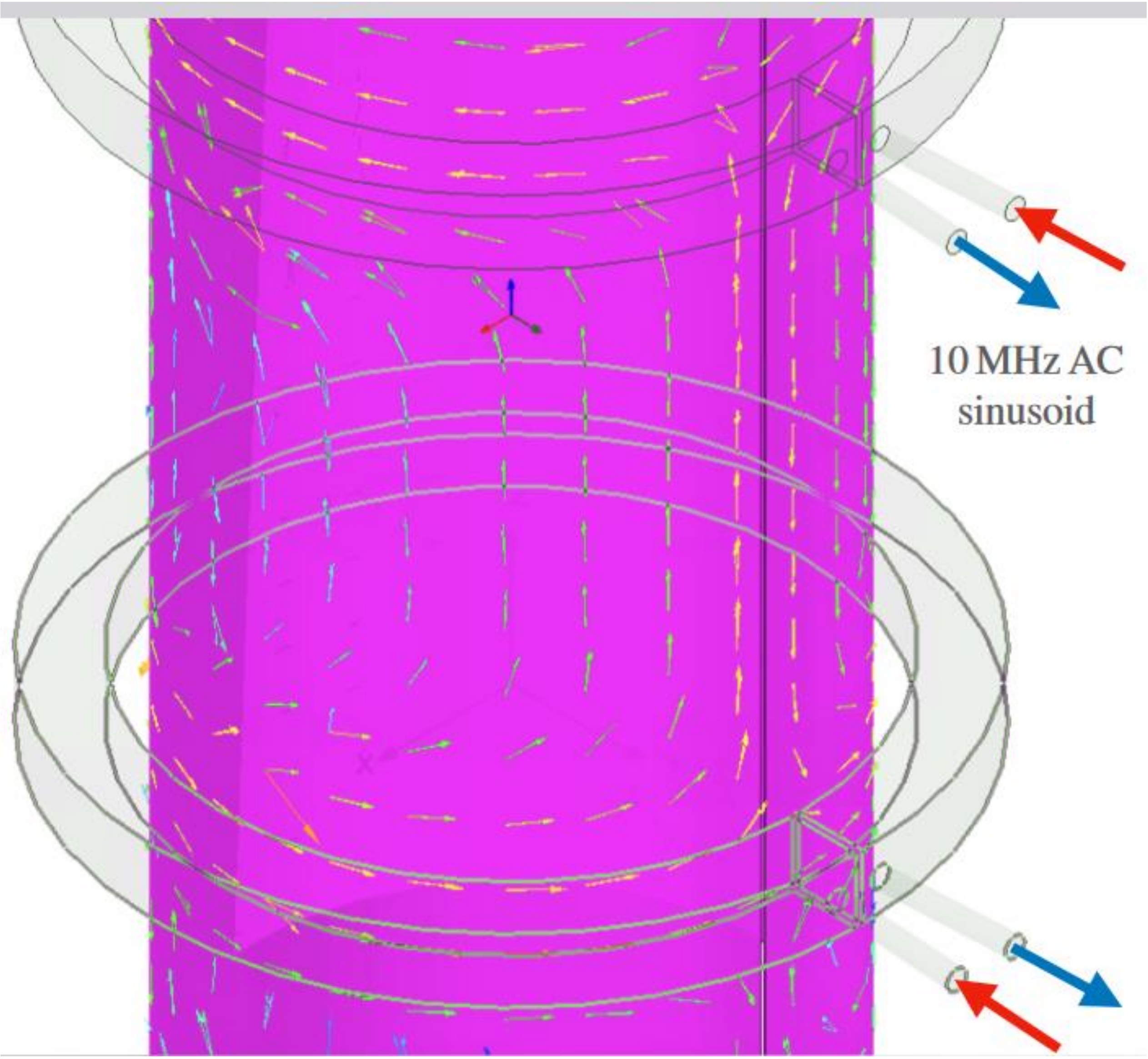
Positron detection for g-2

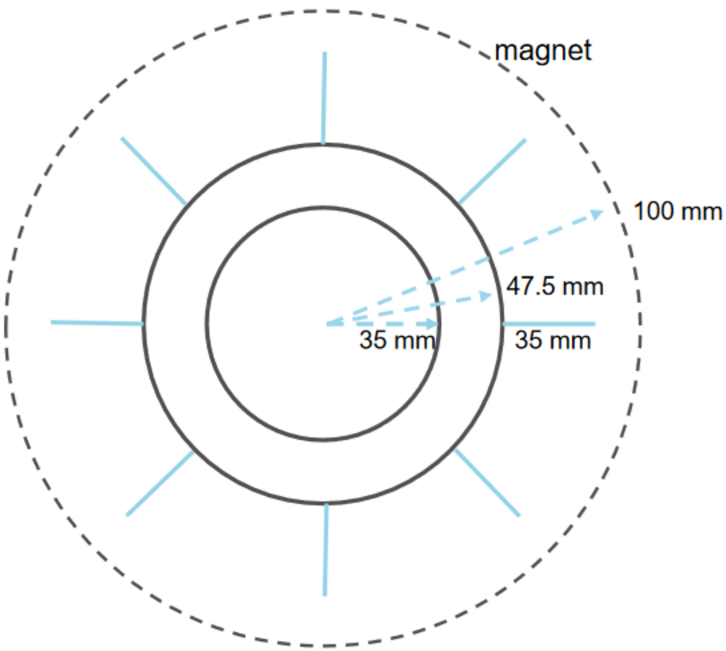
- **Si strip detector for forward-backward asymmetry measurement**
  - ➢2 cylindrical layers (r=35 mm, 47.5 mm) + petals
  - ➢min momentum acceptance – determined by the closeness of the layers to the storage region (30 mm)
  - ➢max momentum acceptance – depends on the longitudinal dimension; p(e+)>58 MeV hit the magnet bore

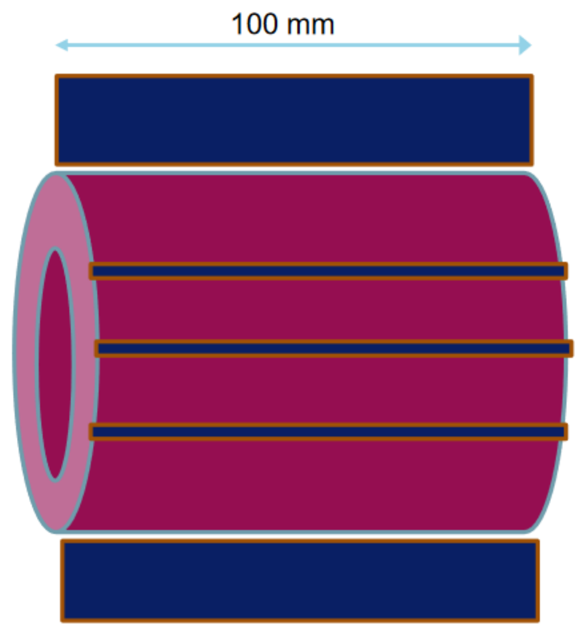




Eddy currents in the electrodes




magnet
100 mm
47.5 mm
35 mm
35 mm


100 mm

Freezing the spin

$$\vec{\omega} = -\frac{e}{m_\mu}\left[\left\{a_\mu \vec{B} - \left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right\} + \frac{\eta}{2}\left\{\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right\}\right]$$