Search for a muon Electric Dipole Moment Using the Frozen Spin Technique

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On behalf of muEDM Collaboration

New Frontiers in Lepton Flavor | Pisa
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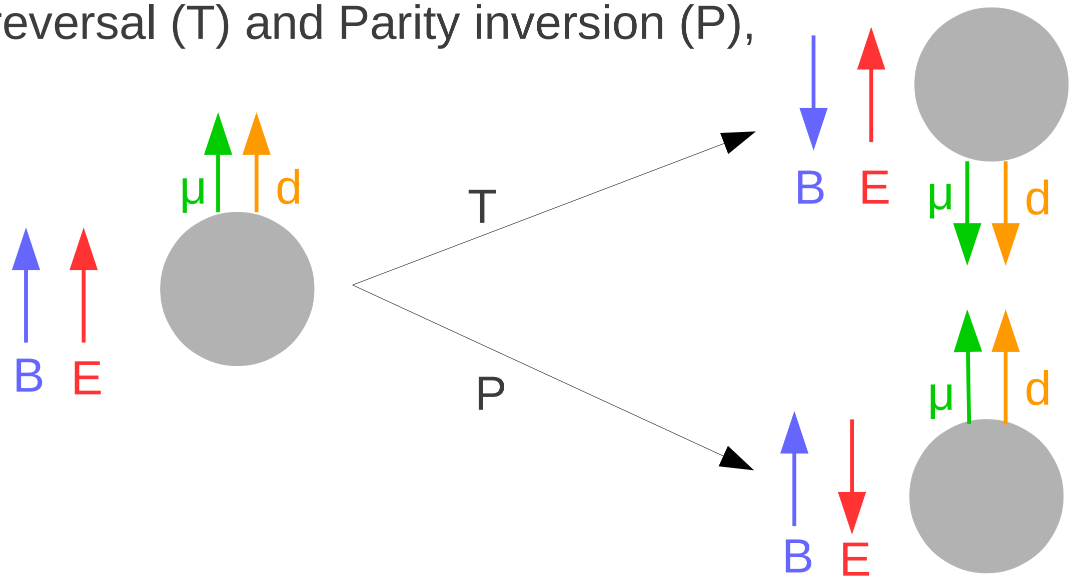
Motivation

- For a fermion in E and B fields,

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

where $\vec{\mu} = g\frac{Qe}{2m_\mu}\vec{s}$ and $\vec{d}_\mu = \eta\frac{Qe}{2m_\mu c}\vec{s}$

- Under Time reversal (T) and Parity inversion (P),



- Assuming CPT invariance, non-zero EDM violates CP symmetry

Motivation

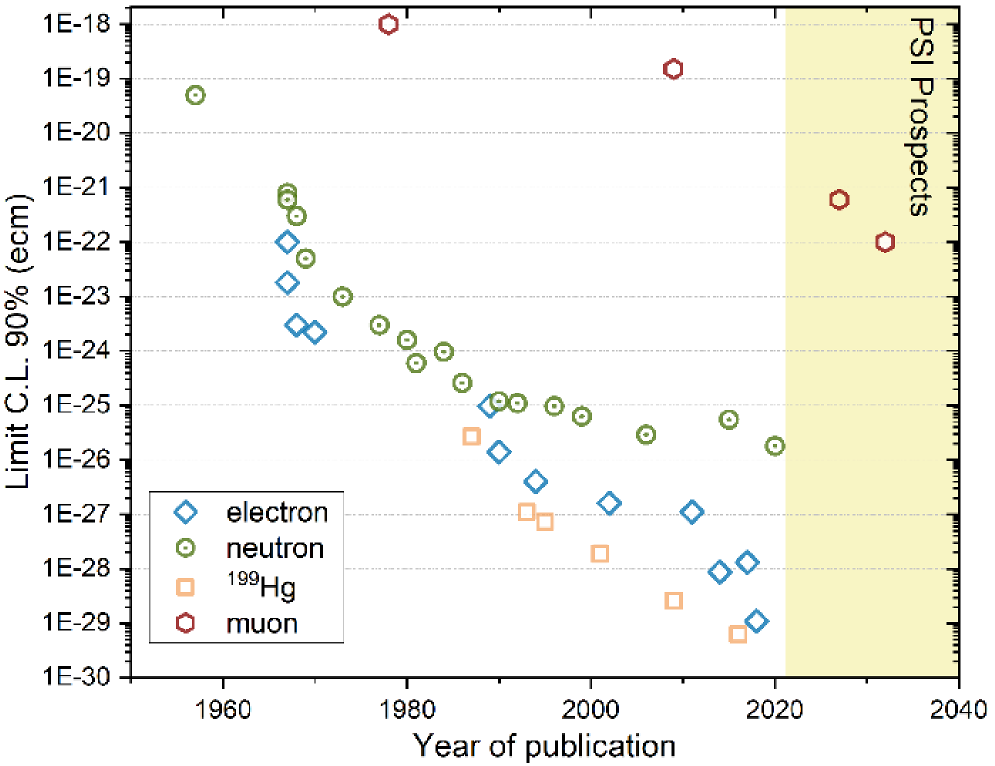
- Standard model of particle physics cannot explain matter-antimatter asymmetry, existence of dark matter and non-zero neutrino masses

- Extensions to SM necessary

- EDM searches provide direct evidence of CP violation

- A dedicated experiment at PSI will experimentally search for muon EDM up to a sensitivity of 6×10^{-23} e.cm

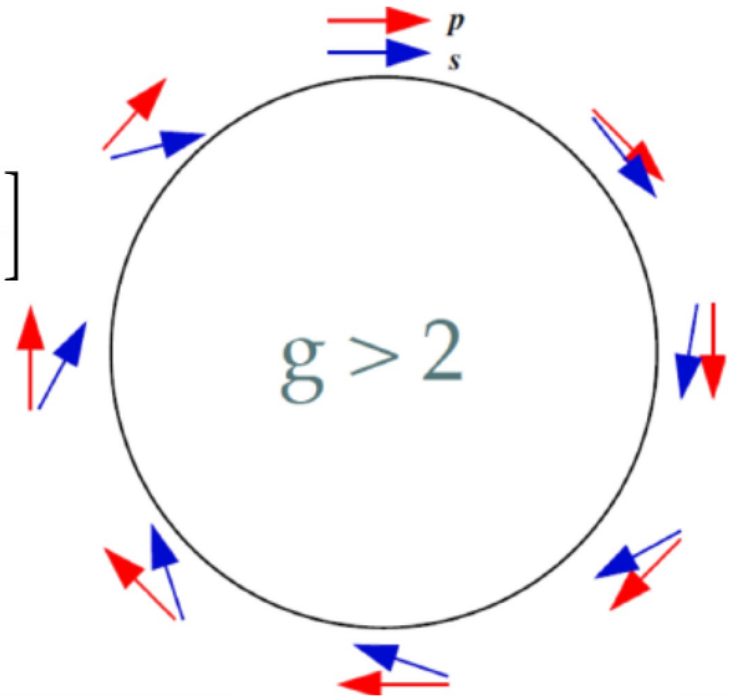
- If not found will improve the current limit by more than 3 orders of magnitude



Muons in Storage Ring

- Spin precession of a muon in a storage ring in E and B fields given by

$$\vec{\Omega}_0 = -\frac{e}{m\gamma}\left[(1+\gamma a)\,\vec{B} - \frac{a\gamma^2}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \gamma\left(a + \frac{1}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$



- Cyclotron frequency is

$$\vec{\Omega}_c = -\frac{e}{m\gamma}\left(\vec{B} - \frac{\gamma^2}{\gamma^2-1}\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

- Anomalous spin precession frequency

$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Muon EDM in Storage Ring

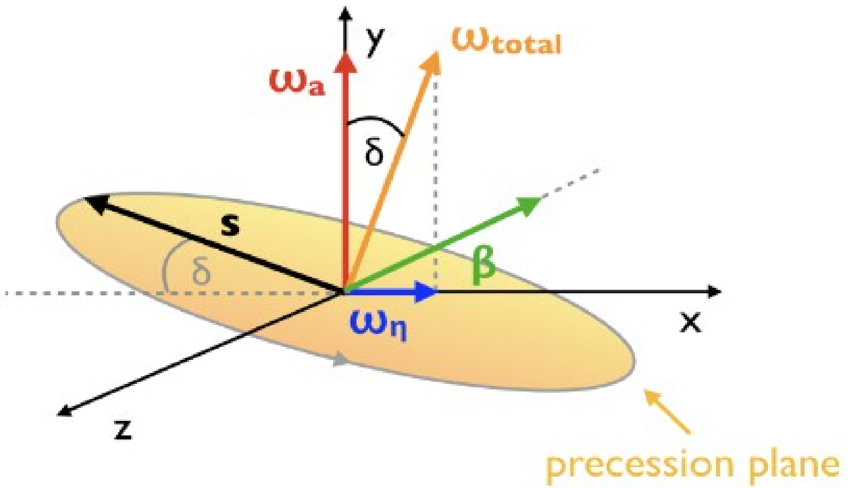
- In presence of an EDM:

$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \underbrace{\frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\text{g-2 term}} + \underbrace{\frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]}_{\text{EDM term}}$$

- A non-zero EDM results in a precession plane tilted out of orbital plane

- In case of magic momentum

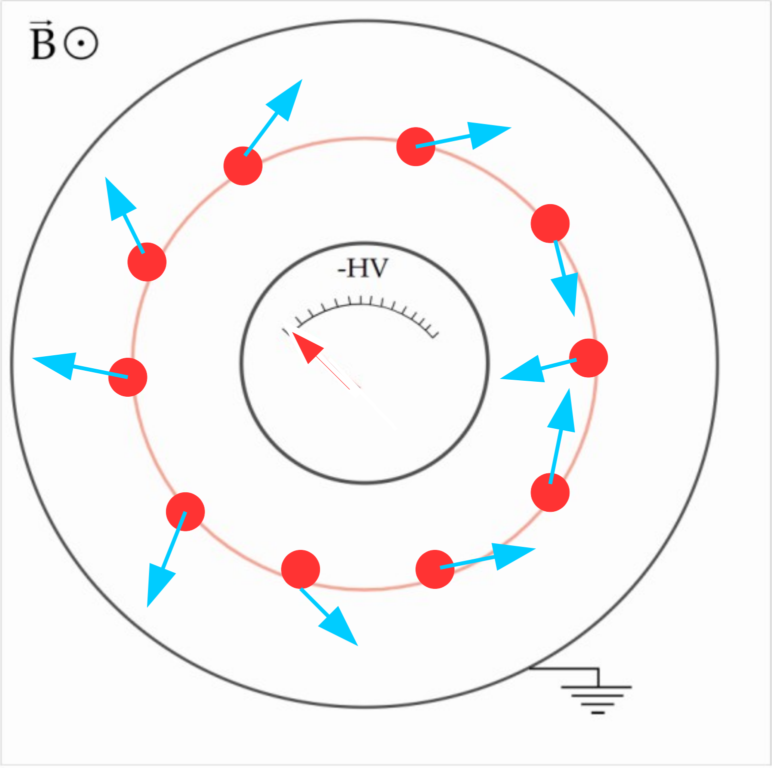
$$\vec{\Omega} = \frac{q}{m}\left[a\vec{B} - \cancel{\left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right] + \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]$$

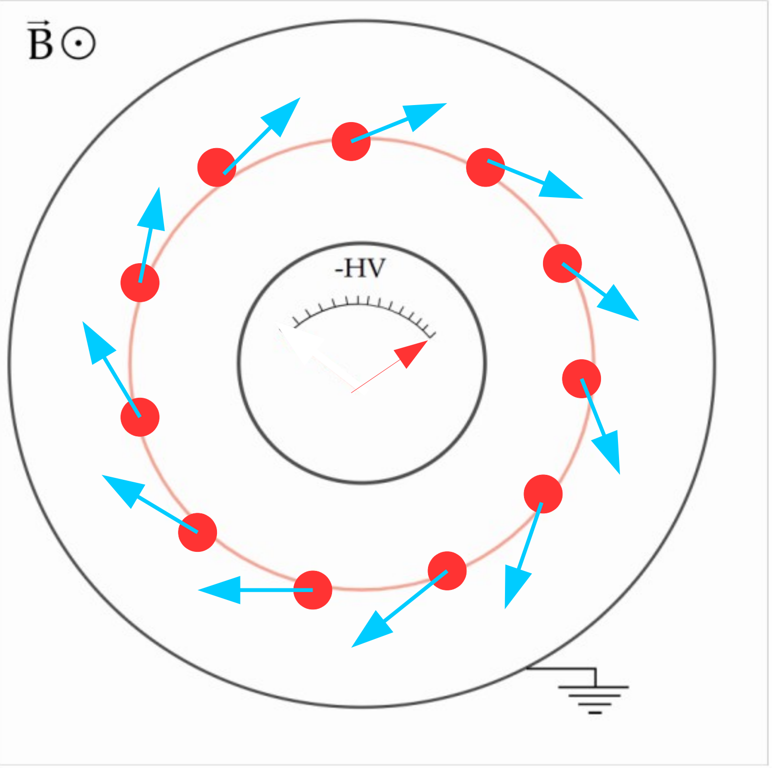


Frozen Spin Technique

- Suppress anomalous spin precession by applying a radial electric field

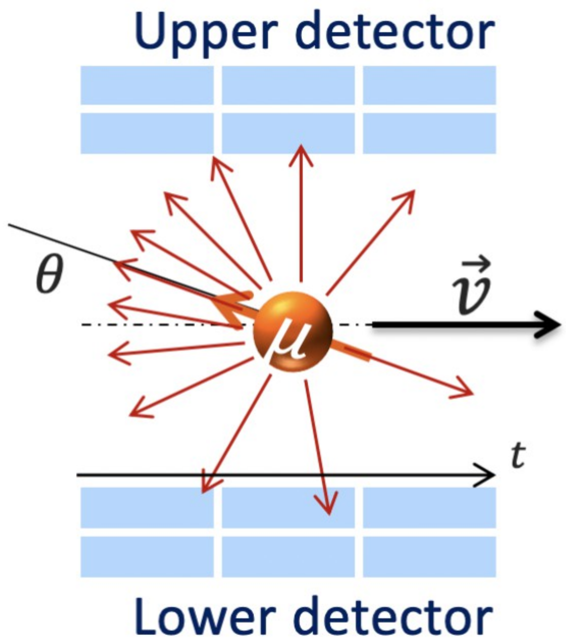
$$\vec{\Omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]$$

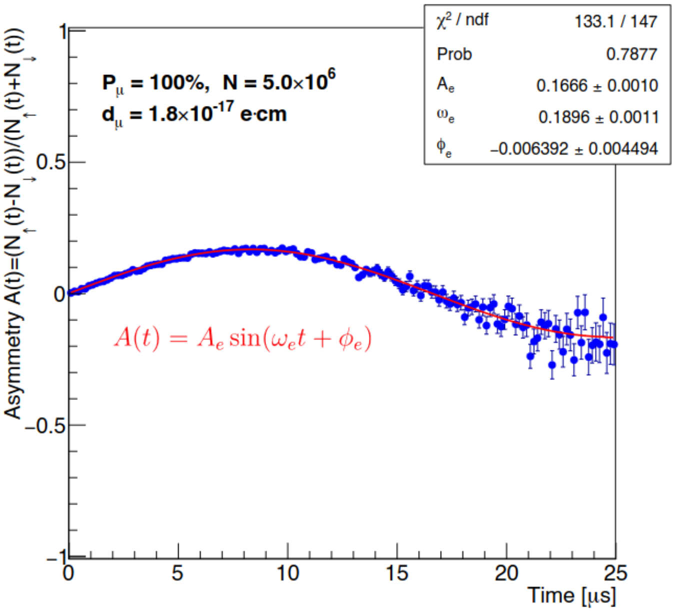




Frozen Spin Technique

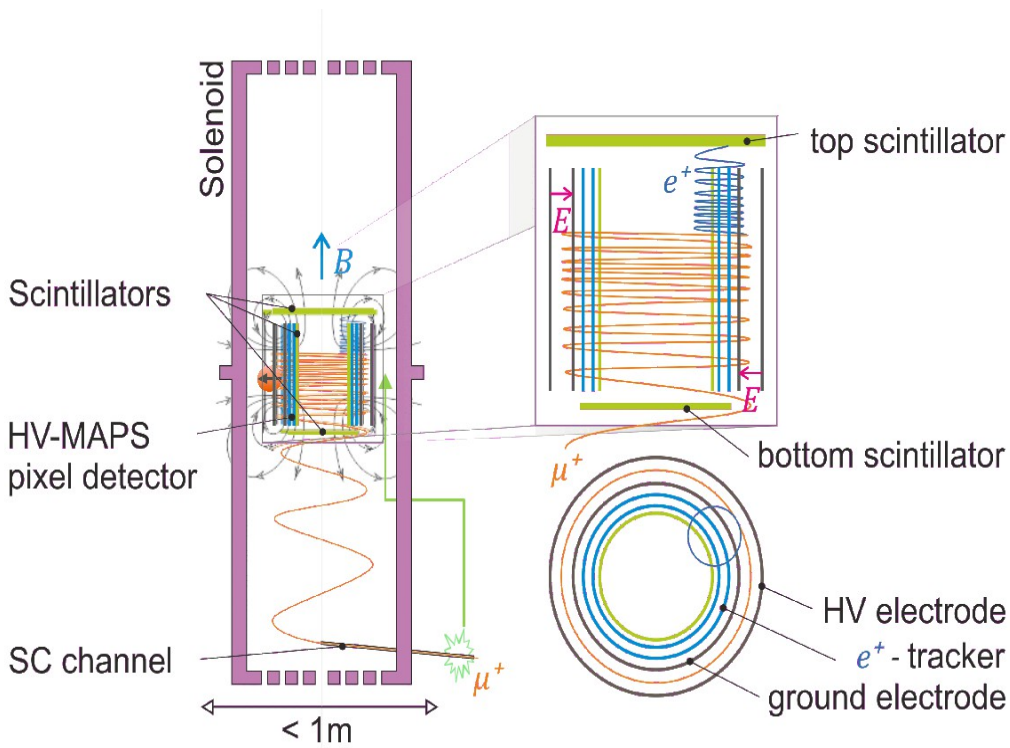
- If EDM = 0, the spin is always parallel to momentum
- If EDM ≠ 0, there is vertical precession out of the plane of the orbit (radial plane)
- Results in up-down directional asymmetry





- Other sources of apparent EDM-like signal from systematic effects
  (see talk by **C. Dutsov** in the next session)

MuEDM Experiment at PSI



- Muons will be injected off-axis in a solenoid (see talk by **A. Doinaki** in next session)
- A entrance detector will be trigger the pulse generator to produce the kick
- The magnetic pulse from the kicker will turn the longitudinal component of muon momentum into transverse plane (see talk by **T. Hume** in next session)
- A coil at the center will produce a weakly focusing field for muon storage
- A radial electric field of E_f = 3 kV/cm is applied in storage orbit region to achieve frozen-spin condition
- Silicon strip in combination with scintillating fiber ribbon track the decay positron to measure the g-2 frequency and longitudinal asymmetry

MuEDM Experiment at PSI

Phase 1

- 28 MeV/c muons from πE1
- Existing PSI solenoid
- Bore diameter 200/300 mm
- Demostrate frozen spin technique

Phase 2

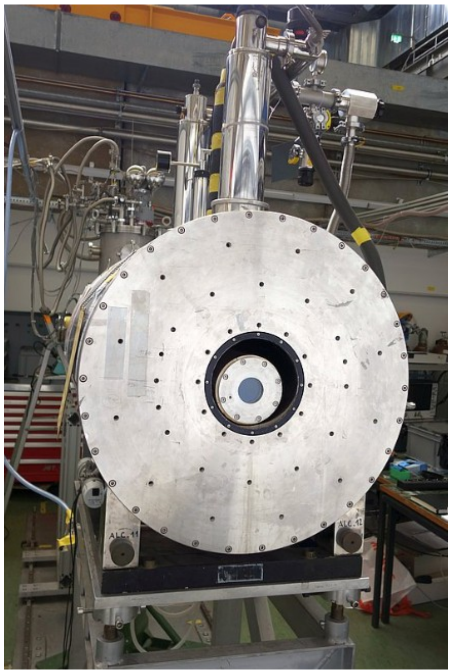
- 125 MeV/c muons from μE1
- Larger magnet upto 900 mm diameter
- Better spatial and temporal field stability

	π**E1**	μ**E1**
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)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

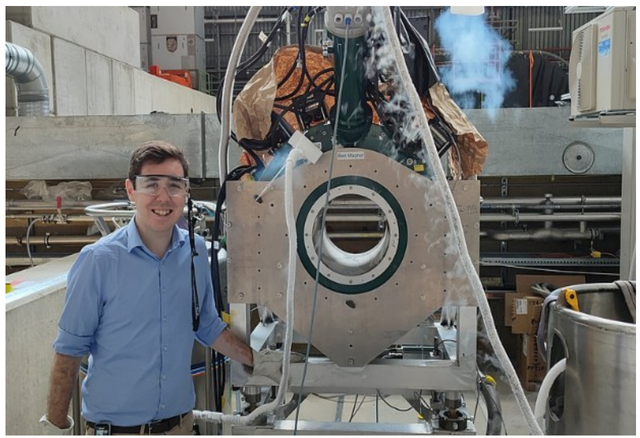
Super-conducting Solenoid

- Two candidates from existing magnets

	PSC	Ben
Max B-Field /T	5	4
Persistent mode	yes	no
Solenoid length /mm	1000	650
Bore diameter /mm	200	300



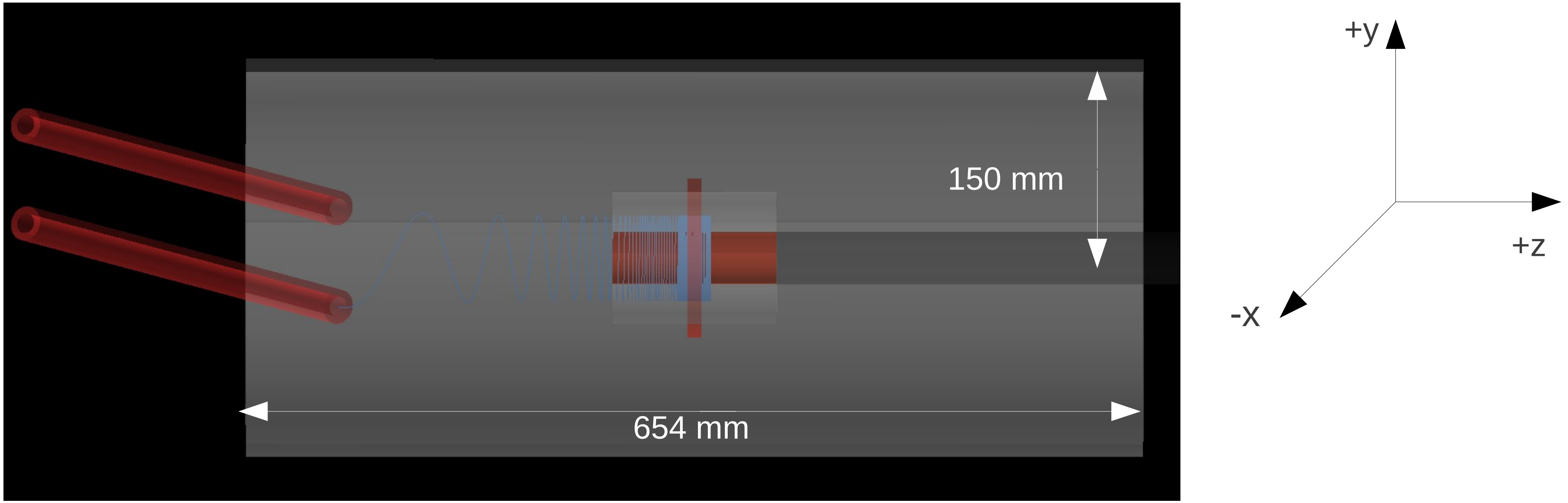
PSC



Ben

- BEN magnet has larger bore diameter
- Better for positron detection

G4Beamline baseline model for BEN magnet

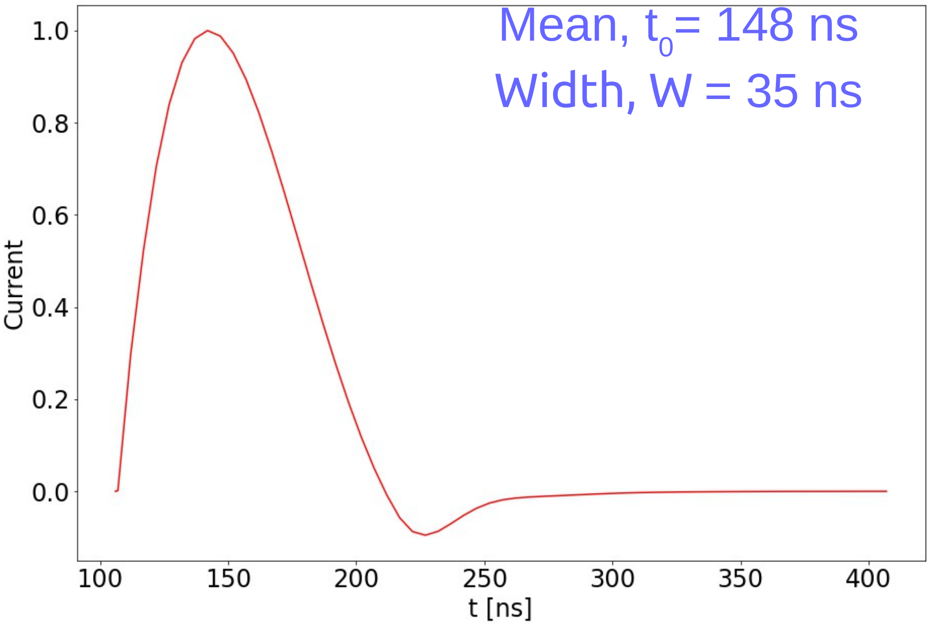


- Best guess injection parameters for storing muons:

  Injection angle, $\theta = 55.69^0$
  Initial injection radius, r = 37.9 mm
  Longitudinal injection coordinate, z = 261.8 mm
  Initial angle on transverse plane, $\varphi = 2.74^0$

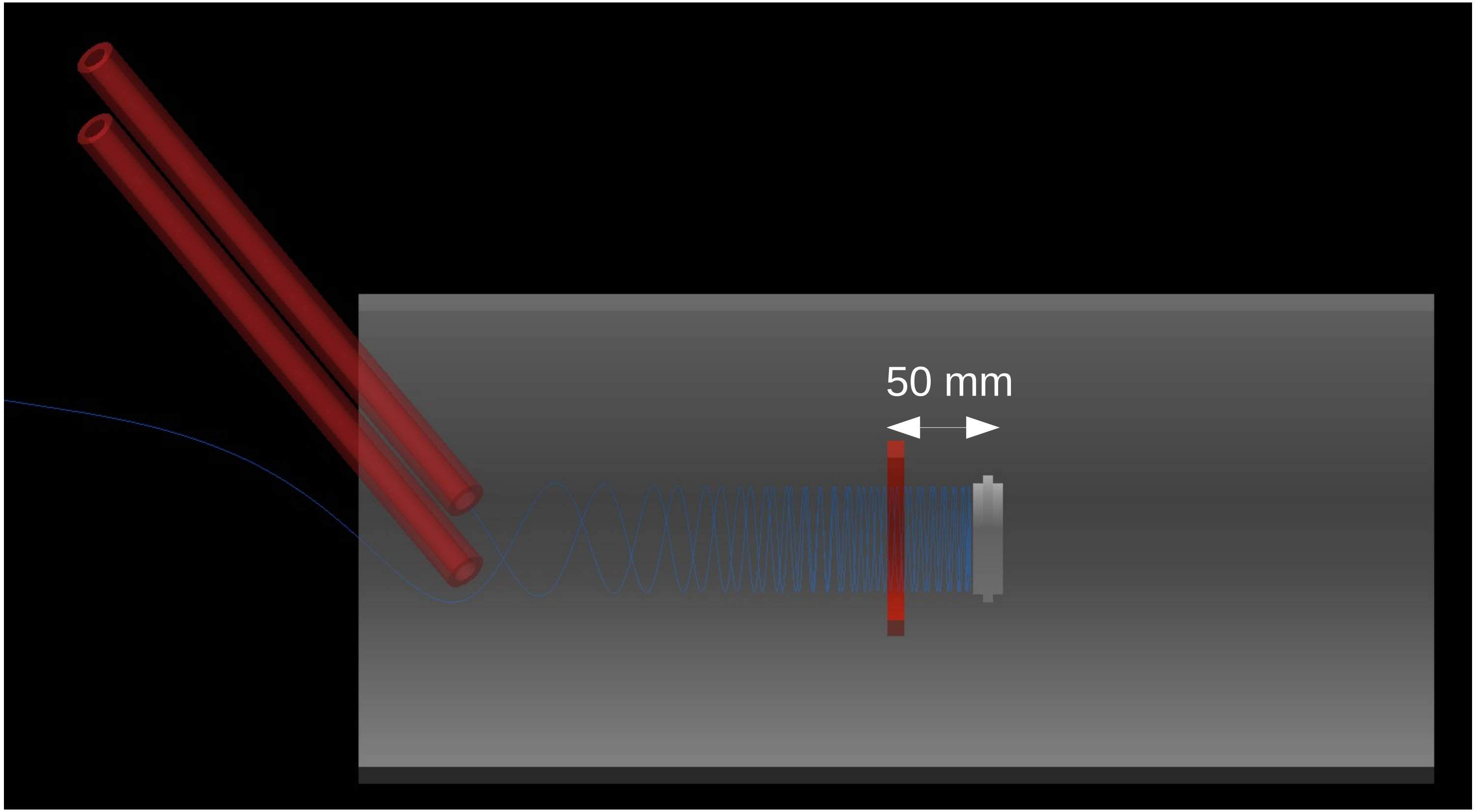
The Kicker Pulse

- The Pulse generator will produce a magnetic pulse to kick the muon's longitudinal momentum into the transverse plane.
- The pulse generator is triggered by signal generated by the muon entrance detector
- This constraints the timing of the pulse generator
- Smaller bore length of BEN magnet imposes tight constraints



Reflecting muons in BEN magnet

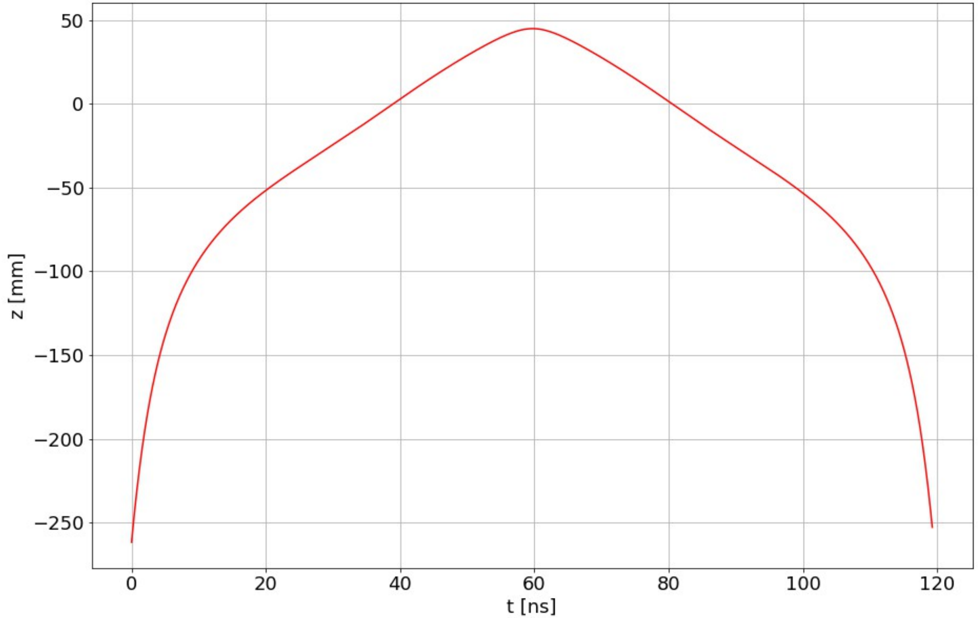
- Tried to add coils in simulations to reflect the muons back to gain more time.

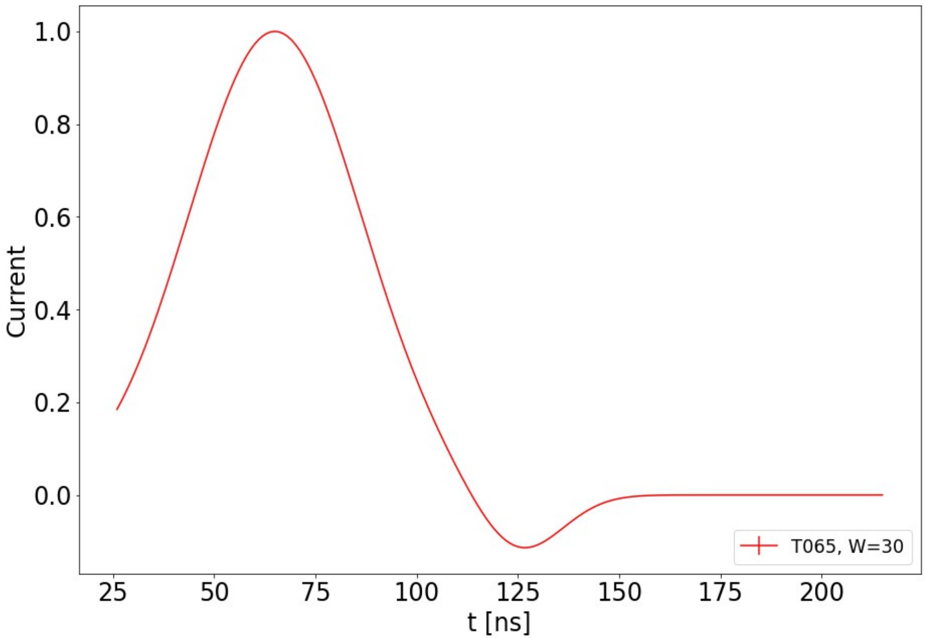


- Configuration of 4 coils producing radial field

Timing requirement for the Kicker pulse

- Simulations with BEN magnet shows extremely tight timing requirements
- For a reference track:

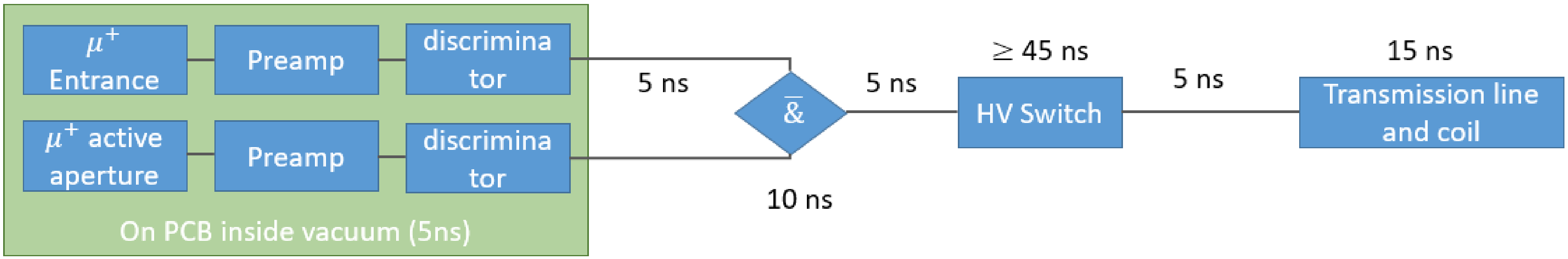




- We need to produce kicker pulse with t_0 ~65 ns

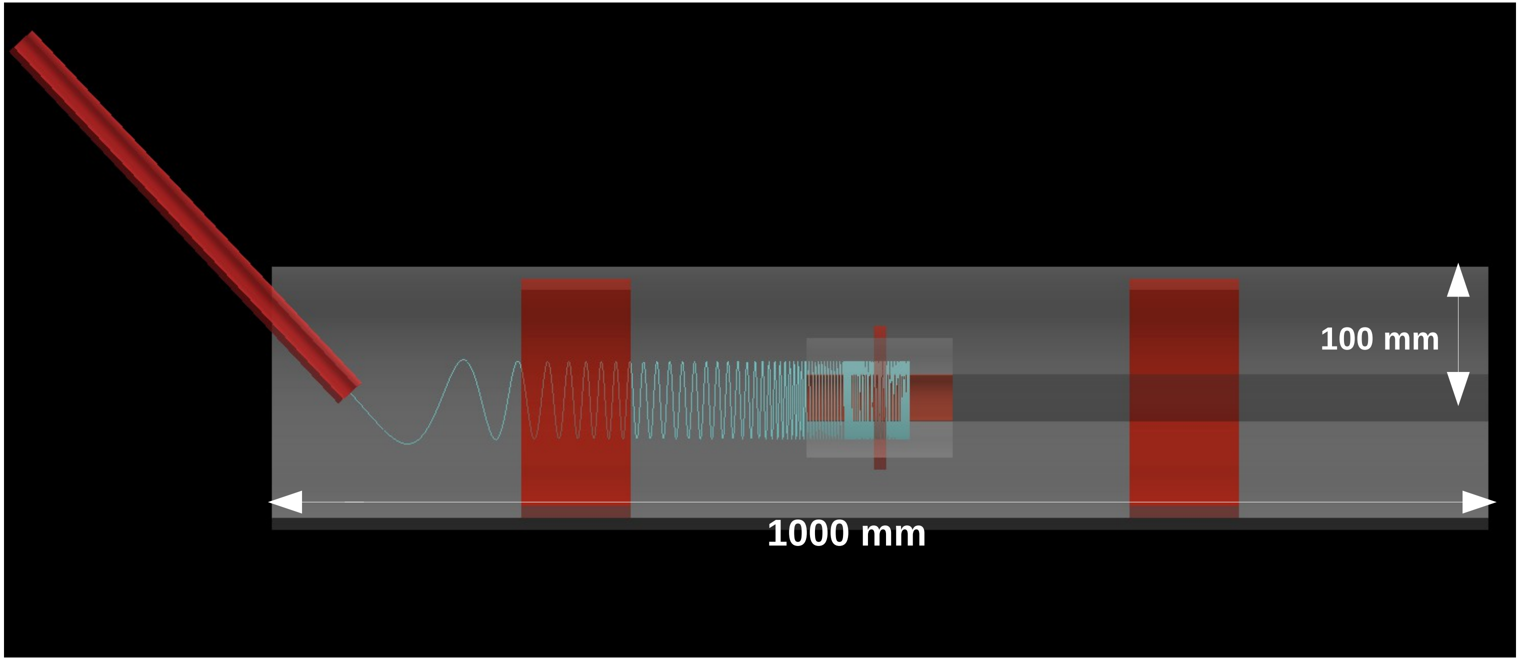
From BEN to PSC

- Timing overview of our kicker system:



- Kicker pulse timing of BEN magnet will be extremely difficult to achieve
- The current requirement for coils for reflecting muons factor of 3 higher than what can be achieved
- Decided to switch to PSC magnet

G4Beamline Simulations for PSC Magnet

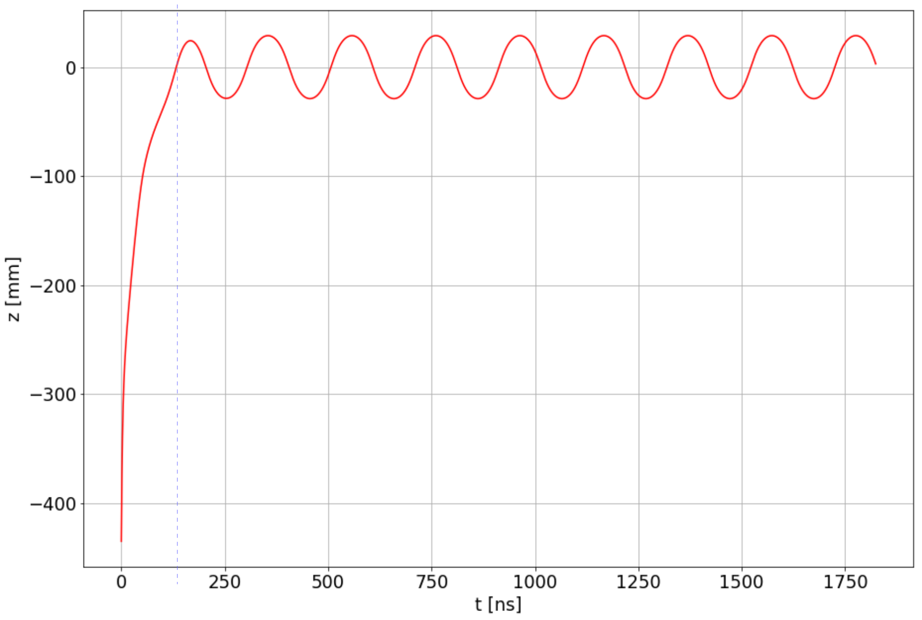


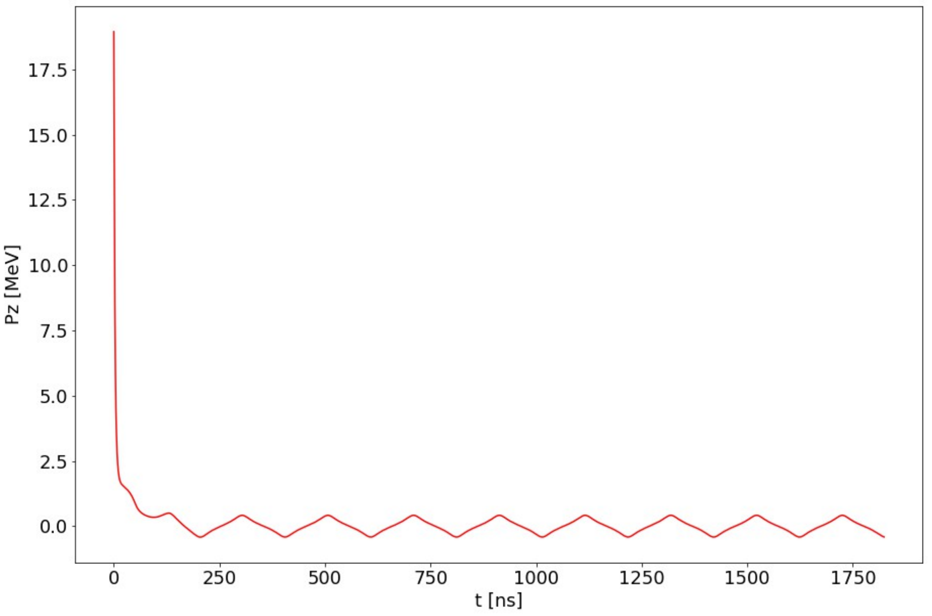
- Best guess initial parameters:
  Injection angle, $\theta = 47.42^0$
  Initial injection radius, r = 40.19 mm
  Longitudinal injection coordinate, z = 435 mm
  Initial angle on transverse plane, $\varphi = 5.65^0$

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

G4Beamline Simulations for PSC Magnet

For a reference particle track:



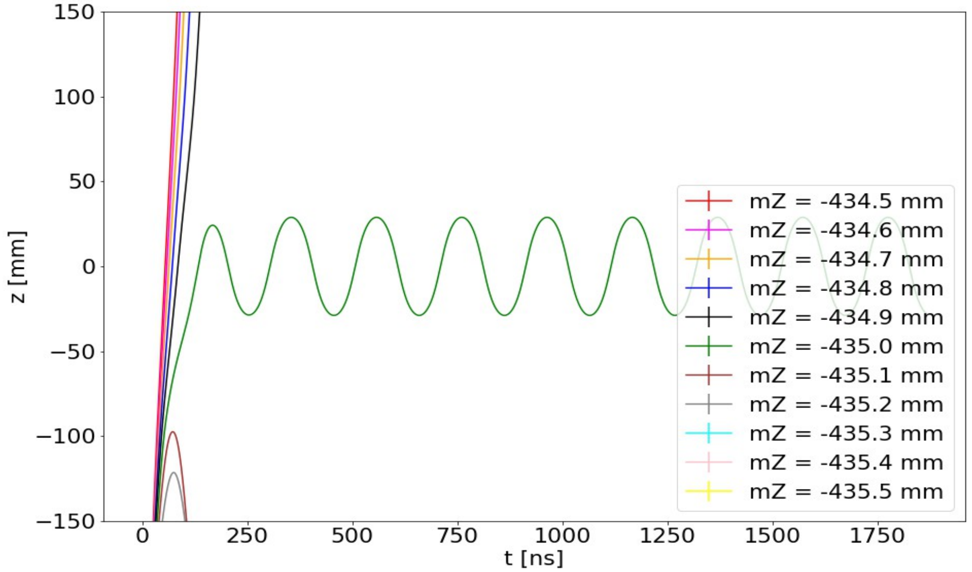


Muons oscillate between z ~ ± 50 mm with longitudinal momentum ~0.5 MeV

Parameters affecting stored muons efficiency

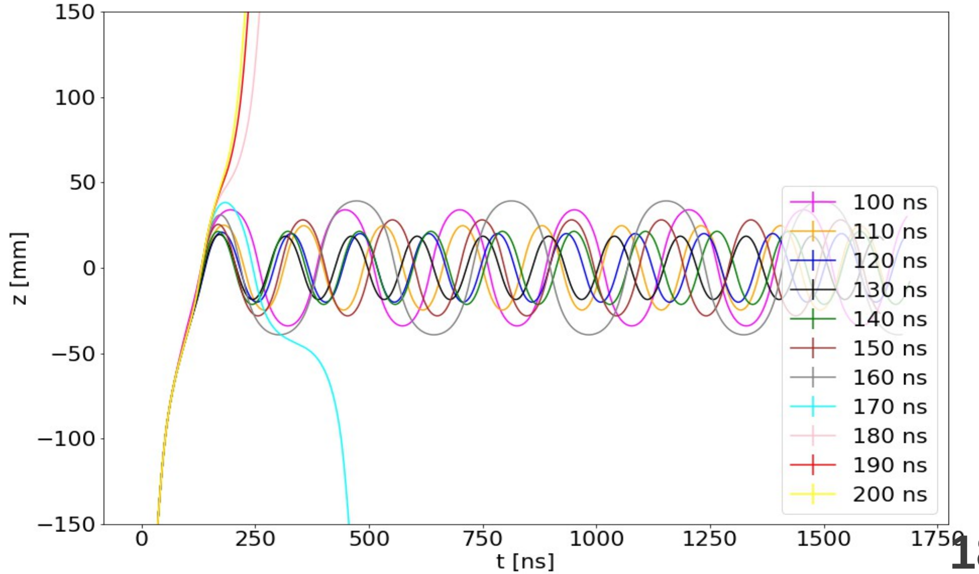
- Number of stored muons is highly sensitive to initial parameters

- Example: initial longitudinal coordinate of muon injection into the solenoid



- Example: The timing of the peak of the kicker pulse

- Amplitude of the oscillation sensitive to timing of the peak



Optimizing the precursor experiment

Parameters affecting stored muons

- Injection angle, θ
- Initial injection radius, r
- Longitudinal injection coordinate, z
- Initial angle on transverse plane, φ

- Timing of the peak on kicker pulse, KPT
- Width of the kicker pulse, W
- Strength of the kicker pulse, BPI
- ...

Using approximated model for optimization problem replacing the real model → surrogate model

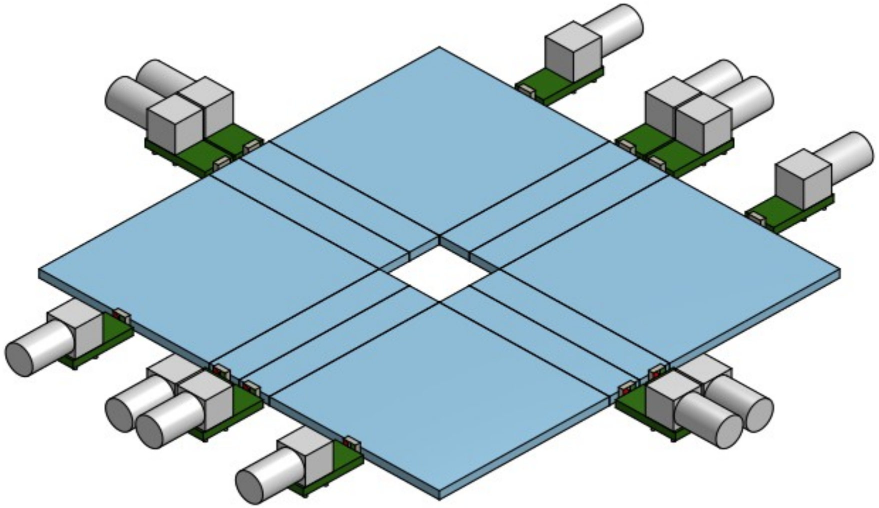
- Create a uniform distribution of the input parameters

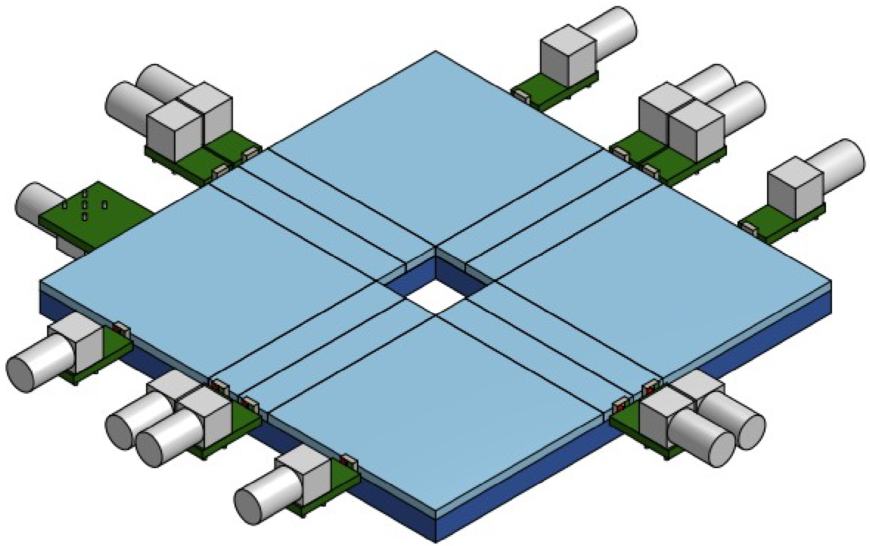
	Theta	Phi	InjR	Z	BPI	KPT	W
0	-47.415000	5.650000	40.200000	-435.000000	-0.800000	145.000000	35.000000
1	-47.402500	5.575000	40.250000	-435.500000	-0.550000	137.500000	45.000000
2	-47.427500	5.725000	40.150000	-434.500000	-1.050000	152.500000	25.000000
3	-47.421250	5.612500	40.225000	-435.750000	-0.425000	156.250000	20.000000
4	-47.396250	5.762500	40.125000	-434.750000	-0.925000	141.250000	40.000000
...	...	...	...	...	...	...	...

- Train surrogate model using the generated distribution
- Fit with various orders of polynomial
- Minimize error test set and model prediction → work in progress

Muon Entrance Monitor

- Focus muon beam onto opening of injection channel
- Scintillator tiles coupled to SiPMs
- Hole in center to let muon beam pass
- Front tile thickness 1-2 mm to stop surface muons
- A thicker (up to ~5 mm) scintillator layer could be added to better discriminate muons and positrons
- Centering procedure optimized in simulation
- Next step, prototype building

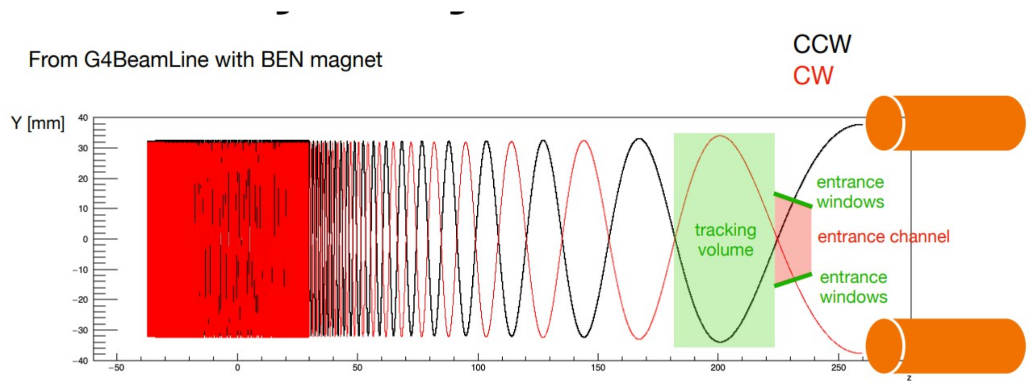


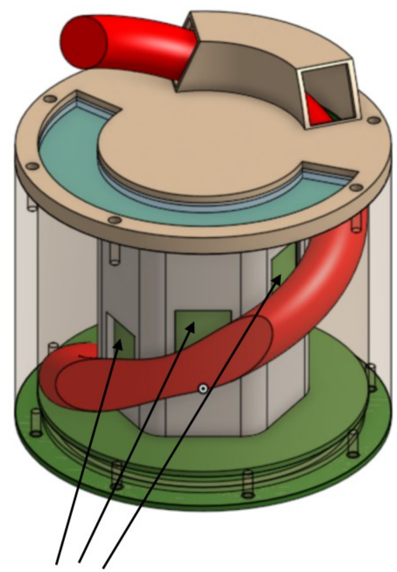


(courtesy L. Morvaj)

Muon Tracking Detectors

- Need to characterize muon trajectory before EDM measurement
- Requires ~ mrad angular and ~0.1% momentum resolution
- Gaseous TPC with 2 geometries possible: longitudinal drift (for momentum), radial drift (for angle).
- Design satisfying constraints with sufficient phase-space acceptance possible with current trajectory parameter
- Resolution of the phase space reconstruction, with realistic ionization and drift properties from beam test measurements and investigation of low pressure gas options



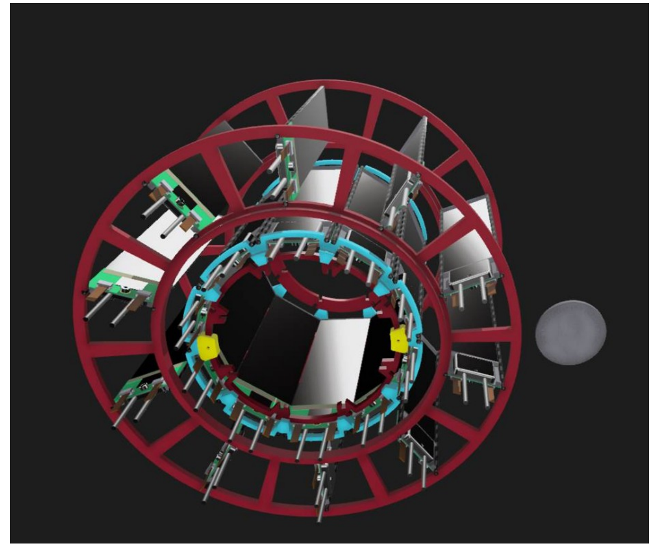


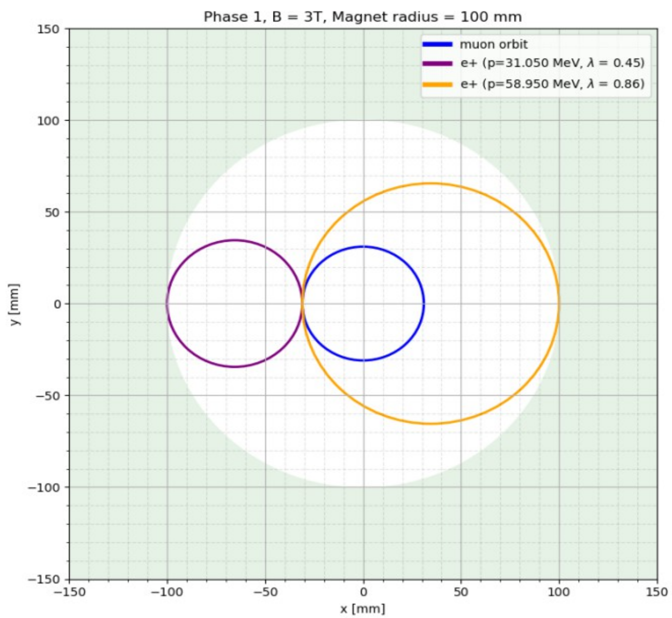
GridPix sensors
(to be duplicated for symmetric CW/CCW tracking)

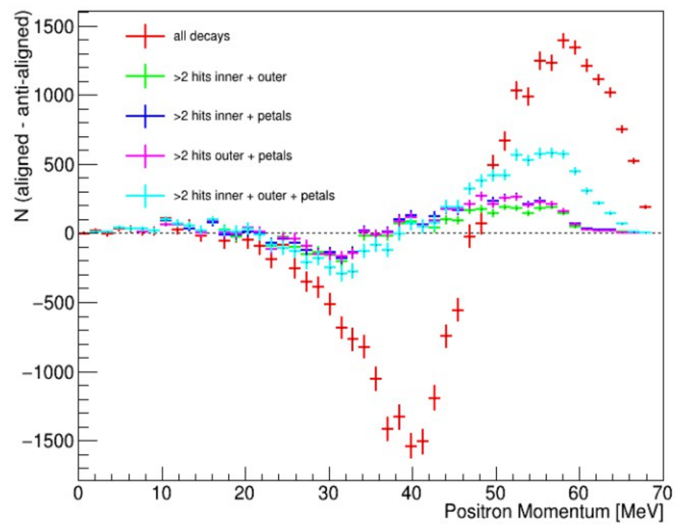
(courtesy F. Renga)

Positron Detection for g-2

- Measurement of g-2 to measure B-field and determine voltage for frozen spin condition
- For Phase I (p = 28MeV) maximum energy is ~68.65 MeV
- Positrons with momentum greater than 59 MeV will hit the magnet regardless of decay direction.
- For (31 < p < 59) MeV positrons it depends on decay direction
- Cylindrical (silicon strip)tracking detectors at r=35 mm,47.5 mm





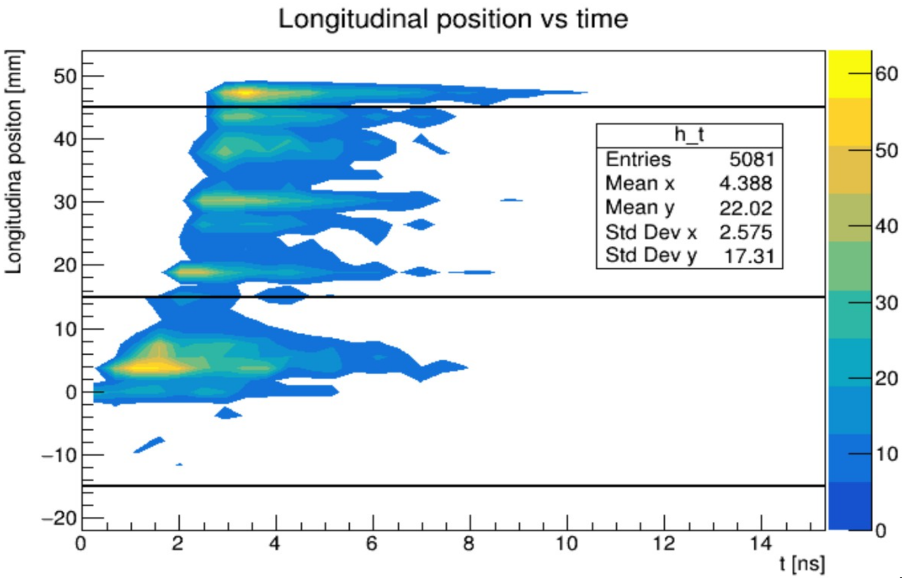


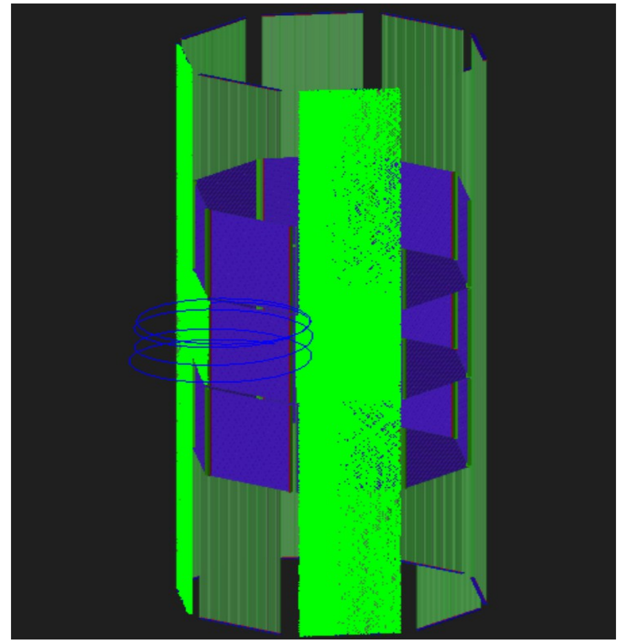
(courtesy J. Price)

- At least 3 hits needed to get a track

Positron Detection for EDM

- For EDM signal, detect up-down asymmetry in photons
- Double barrel Scify tracker, radius of the inner detector currently equal to 50 mm
- Bundles of fibers with good resolution
  - transverse and longitudinal fibers
  - transverse fibers with longitudinal straw/pix





- Photon time and position (longitudinal info on internal barrel)
- Large number of readout channel a challenge
- Considering other possible geometries

(courtesy B. Vitali)

Conclusions and Outlook

- A dedicated experiment to experimentally search for muon EDM is being set-up at PSI
- In case of null result, it will improve the current experimental upper limit by 3 orders of magnitude
- The experiment will take place in two phases, where we will demonstrate the frozen spin technique in phase 1
- Optimization of the design for Phase 1 underway using simulation studies
- Prototype building of important components
- Tested two prototypes of the muon entrance detector in Autumn 2022 beamtime (see talk by **D. Stäger** in the next session)

The Collaboration

Back up

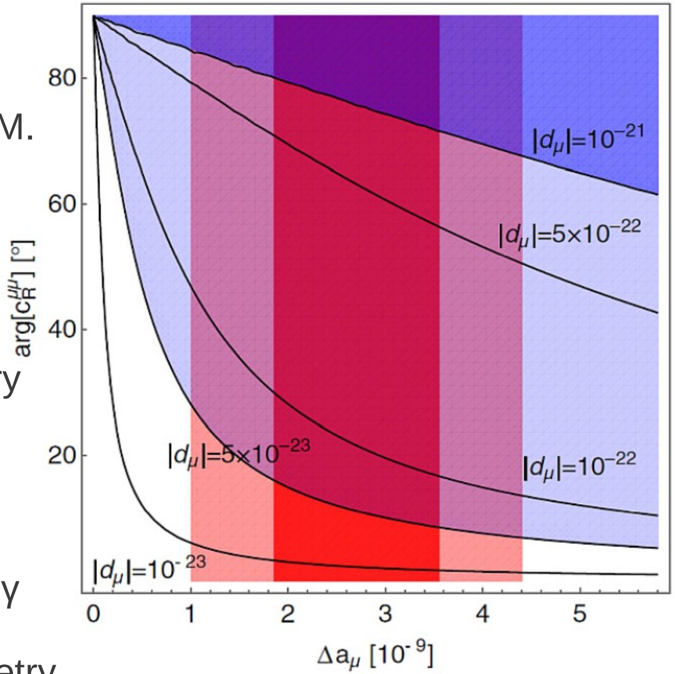
Theory

- No model directly connecting Baryon asymmetry to muon EDM

- In a general EFT, the complex part of Wilson coefficient which might give rise to g-2 anomaly, gives rise to muon EDM. There is no other way of testing this complex part of Wilson Coefficient.

- In MFV within MSSM, simple scaling by the ratio mμ/me predicted, so that electron EDM, de ≤ 1.1×10^−29 e·cm, giving tight limit on muon EDM. But, MFV is ad-hoc symmetry to allow light particle spectra, to reduce fine-tuning in Higgs sector. Does not hold for flavor structure beyond MFV, WC → a phase of order one predicts a sizable EDM

- From a model-building perspective, a key point is that μ → eγ transitions need to be avoided, but this is possible by disentangling the muon from the electron sector via a symmetry, such as a L μ − L τ symmetry which, even after breaking, protects the electron EDM and g − 2 from BSM contributions. Furthermore, it is possible to obtain a significant effect in muon g − 2 and EDM without incurring significant fine-tuning related to the muon Yukawa coupling [47], while the observable consequences of scenarios with large EDMs in h → μμ and Z → μμ could be investigated in future colliders.



Motivation

- In presence of EDM, change in polarization

$$\frac{\mathrm{d}\vec{\Pi}}{\mathrm{d}t} = \vec{\omega}_e \times \vec{\Pi}, \qquad \text{where} \quad \vec{\omega}_e = \frac{\eta q}{2m}\left[\vec{\beta} \times \vec{B} + \frac{\vec{E}_\mathrm{f}}{c}\right] = \frac{2d_\mu}{\hbar}\left(\vec{\beta}c \times \vec{B} + \vec{E}_\mathrm{f}\right)$$

- Longitudinal build-up of polarisation

$$|\vec{\Pi}(t)| = P(t) = P_0 \sin(\omega_e t) \approx P_0 \omega_e t \approx 2P_0 \frac{d_\mu}{\hbar}\frac{E_\mathrm{f}}{a\gamma^2} t.$$

Slope, $\frac{\mathrm{d}P}{\mathrm{d}d_\mu} = \frac{2P_0 E_\mathrm{f} t}{a\hbar\gamma^2}$

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

(scaling by 1/ N for the Poisson statistics of N observed muons and A is mean decay asymmetry)

- In a magnetic field of 3 T this results in an EDM sensitivity for a single muon of σ(dμ) ≈ 2×10 −16 e·cm and σ(dμ) ≈ 5×10 −17 e·cm, for πE1 and μE1 respectively, which in turn results in an electric field for the frozen-spin condition of E f = 0.3 MV/m and E f = 1.9 MV/m, respectively.

Systematics

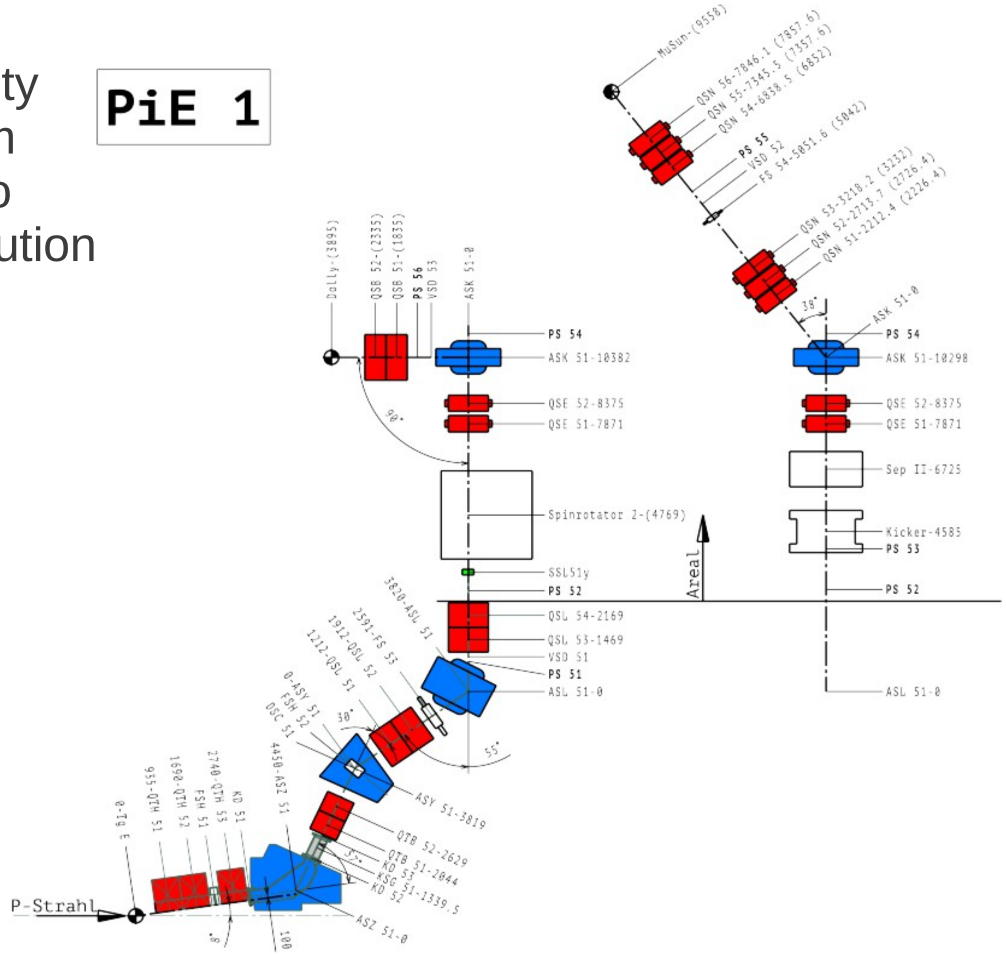
Systematic effect	Constraints	Phase I		Phase II	
		Expected value	Syst. ($\times 10^{-21}$ $e\cdot$cm)	Expected value	Syst. ($\times 10^{-23}$ $e\cdot$cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ µm	0.75	$\Delta_R < 7$ µm	1.5
Electrode local smoothness (longitudinal E-field)	Local longitudinal electrode smoothness	$\delta_R < 3$ µm	0.75	$\delta_R < 0.7$ µm	1.5
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$	< 50 ns	0.5
Net current flowing muon orbit area	Wiring of electronics inside the orbit	< 10 mA	$< 10^{-2}$	< 10 mA	0.3
Early-to-late detection efficiency change	Shielding and cooling of detectors	–		–	
Resonant geometrical phase accumulation	Misalignment of central axes	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}	Pitch < 1 mrad Offset < 2 mm	0.15
TOTAL			1.1		2.2

Table II: Summary of systematic effects for both phases of the experiment. The determination of the effects related to early-to-late detection efficiency changes will be completed before the end of 2023.

Muon Trajectory

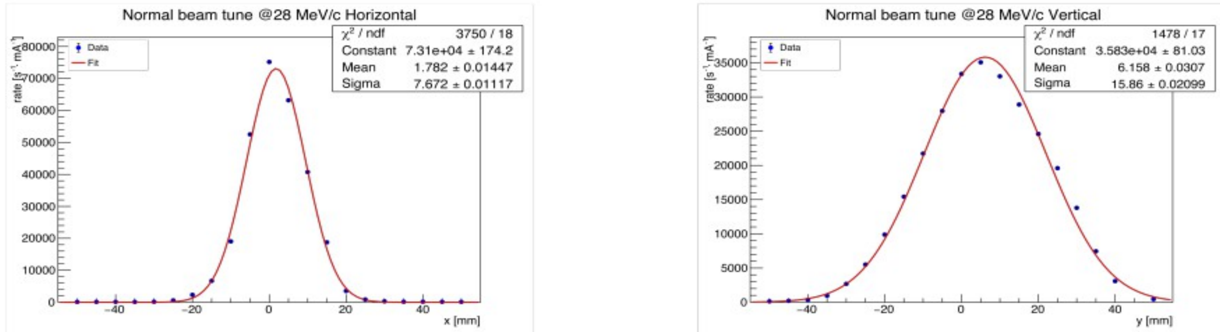
- The πE1 beamline is a high-intensity pion and muon beamline with beam momenta ranging from 10 MeV/c to 500 MeV/c and a momentum resolution of better than 0.8 %.

PiE 1



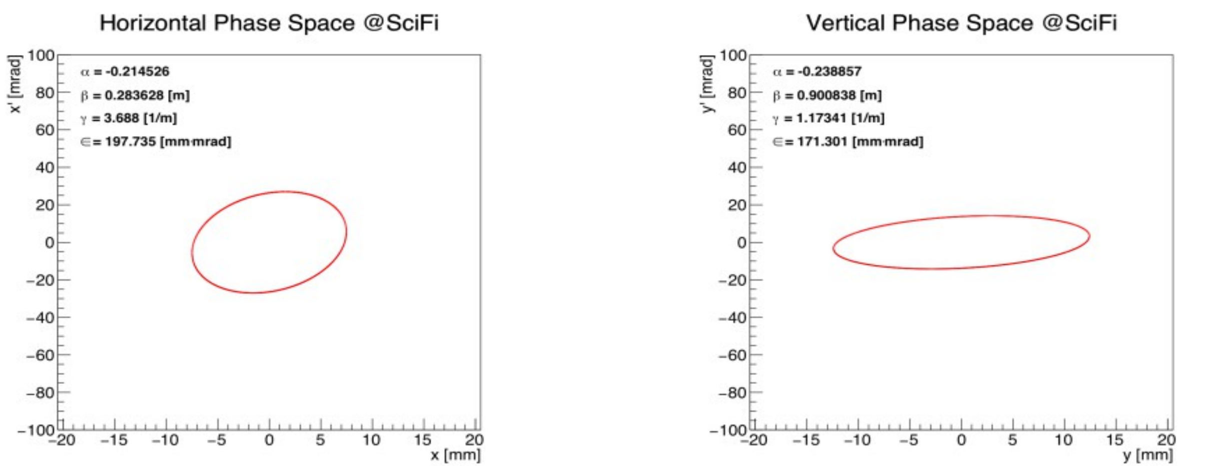
Muon Phase Space

- The measurements were performed for a positive muon beam momentum at 28 MeV/c with two different beam tunes, the so-called “normal” beam tune and “inverted” beam tune. Both beam tunes were tested to maximize the muon beam intensity and minimize the transverse beam size at the beam focus.
- We measured the transverse beam profiles simultaneously in x- and y-directions by integrating the count rate of each fiber over 10 s using the SciFi detector, see Fig. 13. The flux of R = 4.5 × 10 6 μ + /s at a proton current of 1.6 mA was calculated by integrating over all fibers in each direction and taking the average.
- Since the entire setup was placed in vacuum, the horizontal and vertical beam widths were determined directly by fitting a Gaussian to the time-averaged profiles and the 1 − σ value of the distribution was used as true beam width.



(a) (b)

Figure 13: Measured horizontal (a) and vertical (b) muon beam distribution at 28 MeV/c for πE1_2



(a) (b)

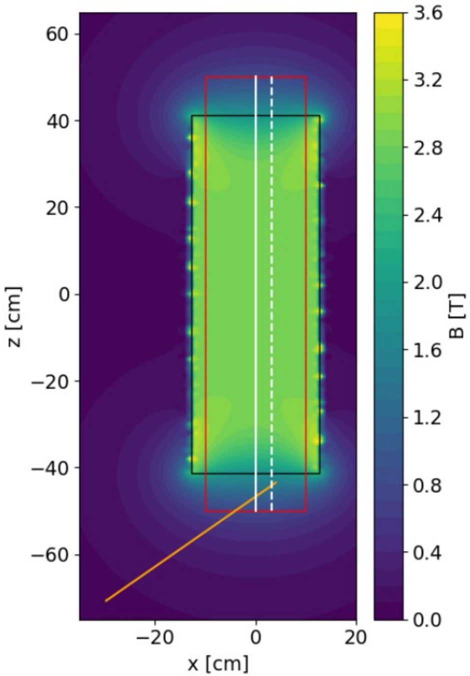
Figure 14: Measured horizontal (a) and vertical (b) phase space Twiss parameters for 28 MeV/c muons for πE1_2

Muon Phase Space

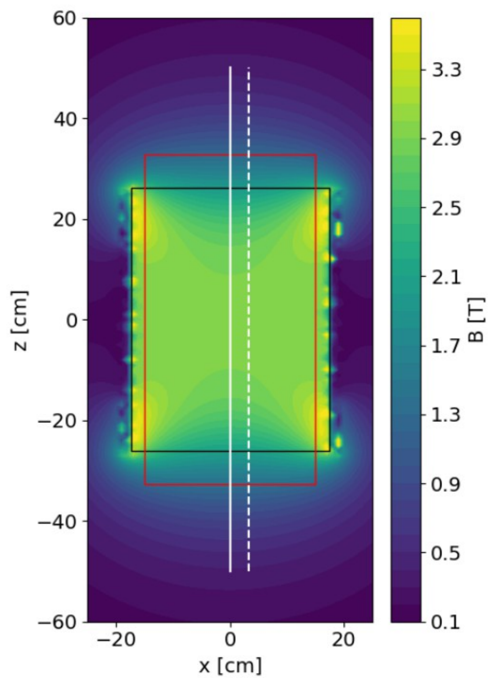
	Twiss parameters and emittance	
Horizontal phase space	α_x	-0.21
	β_x / m	0.28
	γ_x / m^{-1}	3.69
	ϵ_x / π mm mrad	198
Vertical phase space	α_x	-0.21
	β_x / m	0.28
	γ_x / m^{-1}	3.69
	ϵ_x / π mm mrad	171

Table III: Twiss parameters of the πE1_2 beamline at 1444.25 mm downstream of the final quadrupole QSN56 and transverse beam emittance for the normal setting of the transfer line.

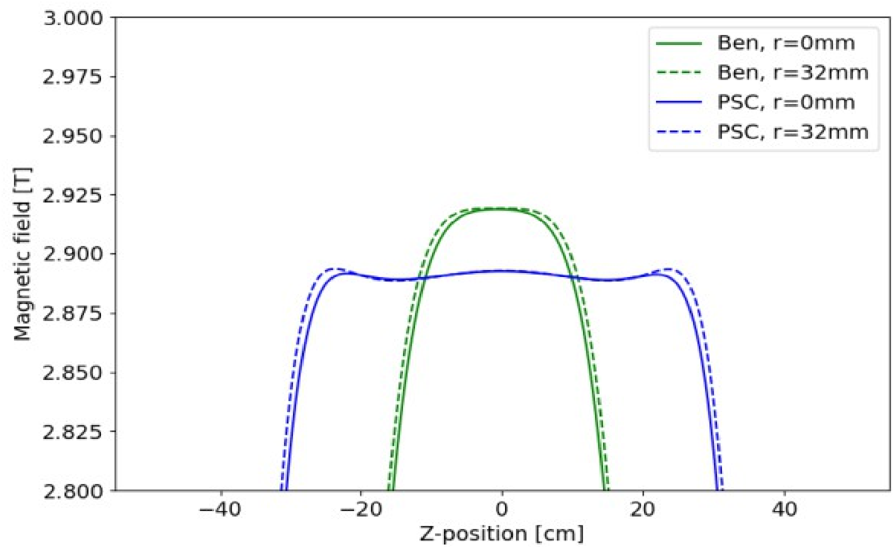
Magnetic field maps



PSC



BEN



(a)

Entrance monitor

- The center of the beam passes through the central hole the size of the injection tube (~15 mm diameter, corresponding to approximately 2σ around the center of the beam), while the tails of the beam are measured using scintillators coupled to silicon photo-multipliers (SiPM)s.
- The scintillator segments will monitor muon intensity and position.

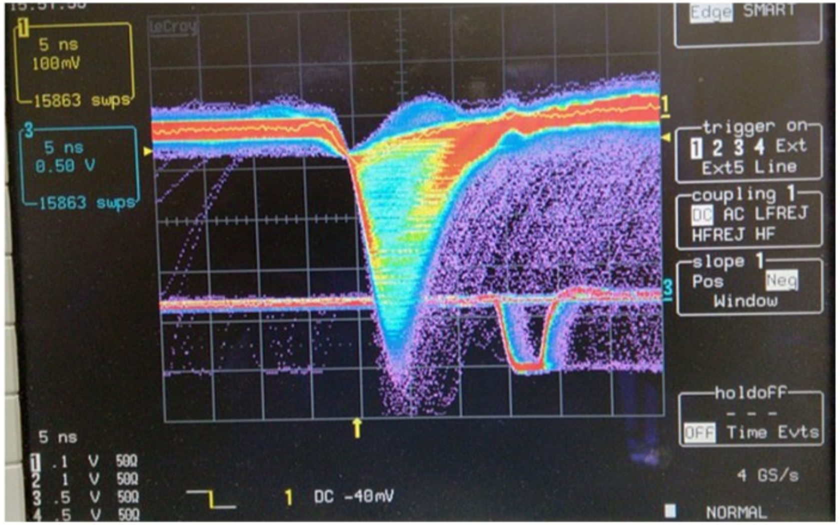


Figure 21: An image demonstrating the discrimination power between muons and positrons. A 2 mm thick plastic scintillator is placed in the beam containing particles with the momentum of 28 MeV/c. Positrons, being minimum-ionizing particles, deposit much less energy than muons, resulting in lower-amplitude pulses.

Trajectory tracker

Injection angle

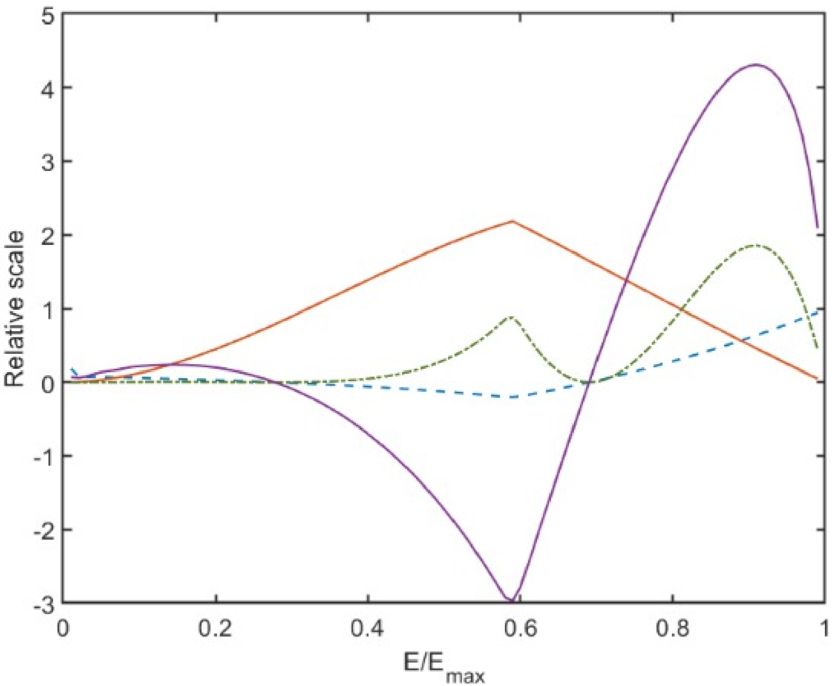
- GridPix is a gaseous detector made of a conductive mesh implanted 50 μm above a Timepix chip
- The measurement of the longitudinal injection angle is the most affected by the beam-matter interaction because of multiple Coulomb scattering (MS).
- A gaseous detector with an extremely light gas mixture and an extremely thin, vacuum-tight entrance window is necessary and, even with the lightest gas mixture one can reasonably foresee, the angular information would be spoiled after a few centimeter.
- With such a short lever arm, a single-hit resolution of O(100 μm) is necessary to reach O(1 mrad) angular resolution.
- The optimal solution for this application is a Time Projection Chamber (TPC) with the high granularity readout provided by GridPix.
- One hit per electron → a spatial resolution only limited by the pixel size (50 μm) and the diffusion in the drift region
- Phase 1 → MS in the entrance window is likely to give the dominant contribution to angular resolution
- Phase 2 → higher momentum → less MS → easier to achieve target resolution for angle

Momentum

- Muon momentum can be precisely measured by a conventional longitudinal TPC placed right after the GridPix-TPC or installed as a standalone detector.
- The muons will enter through a thin window, on the cathode side. In this case, the thickness of the window is less problematic because energy loss fluctuations can be kept well below the target resolution of 0.5% even with a relatively thick foil.
- The muon will make at least one full turn inside the active volume, before exiting from the anode side, in order to maximize the sensitivity to the curvature radius.
- Ionization electrons will drift along the longitudinal axis, and will be collected by a gas multiplication and readout
- Single-hit resolution will be dominated again by diffusion. With an appropriate mixture, the diffusion coefficient can be kept well below 500 μm/ √ cm, so that the required resolution on a 30 mm curvature radius can be ensured by the high number of hits that is expected even with the lightest gas mixtures.

g-2 detection

- combine a scintillating fiber-based detection scheme with a silicon strip detector.
- timing provided by scintillator technology
- complementarity of two independent schemes for tracking
- silicon based tracker is preferable to a straw-based tracker → timing resolution for silicon strip detectors of limited thickness is 2 ns, for straw detectors it is 60 ns → positron orbit time for a 1 ns → a hit in the same strip will be difficult to distinguish → impossible for straw detector
- Each detector hit causes an average loss in energy of approximately 50 keV per 100 μm of silicon
- The variation in the number of decay positrons as a function of momentum is the difference between the pμ · ŝ = 1 and −1

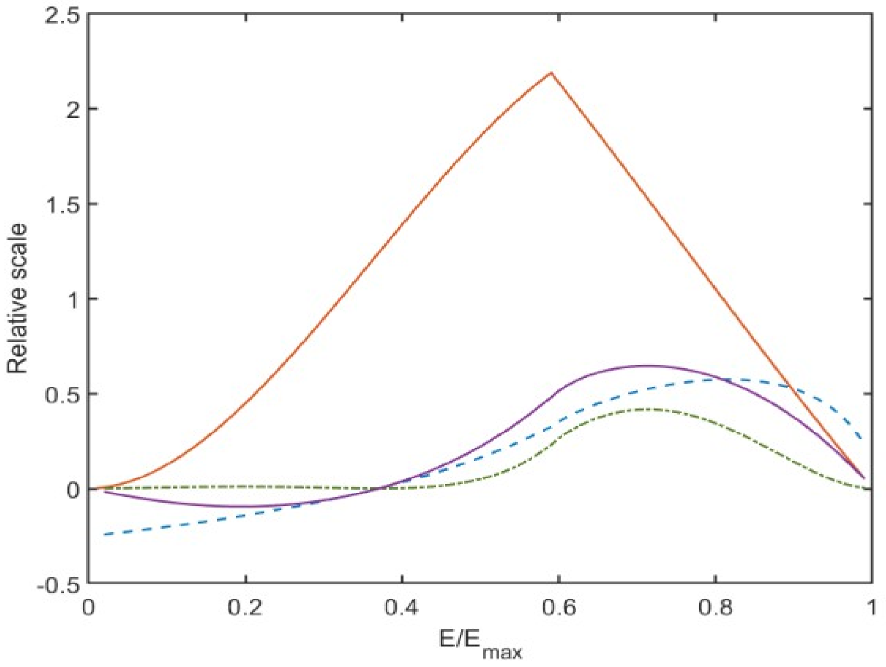


Momentum: a few MeV/c. This is mainly necessary to choose positrons with the desired asymmetry, which is shown to be momentum dependent, as illustrated in Fig. 31.

Position: Taking into account multiple scattering, a resolution of around 1 mm is sufficient for the fitting of the tracks with the required uncertainties in the direction. This result was achieved by geometric means, assuming that reliable timing information is available [71].

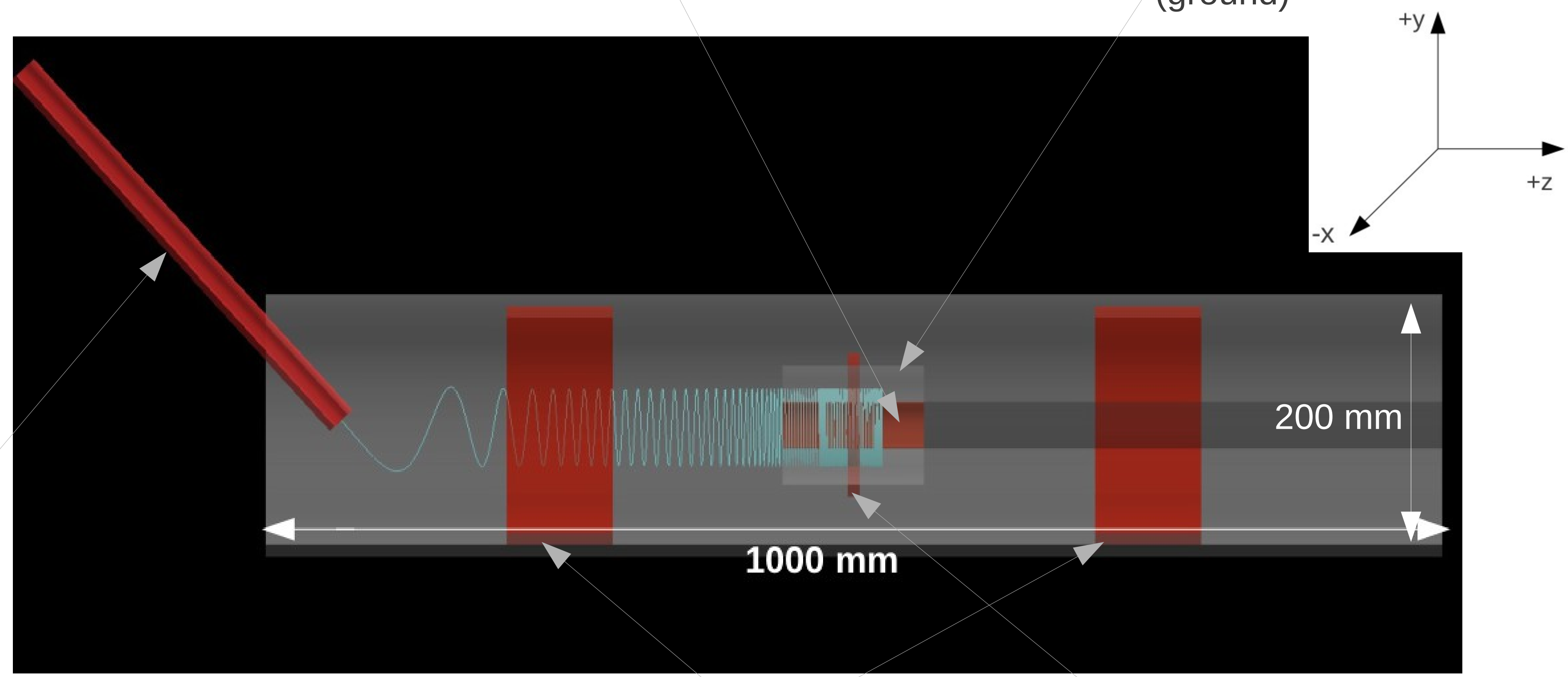
Time: less than 1 ns. A positron from the decay of a 28 MeV/c muon travels at c, which means that in the magnetic field of 3 T a complete rotation takes $\lesssim 0.6$ ns. This imposes a limit on the resolution of the timing.

EDM detection



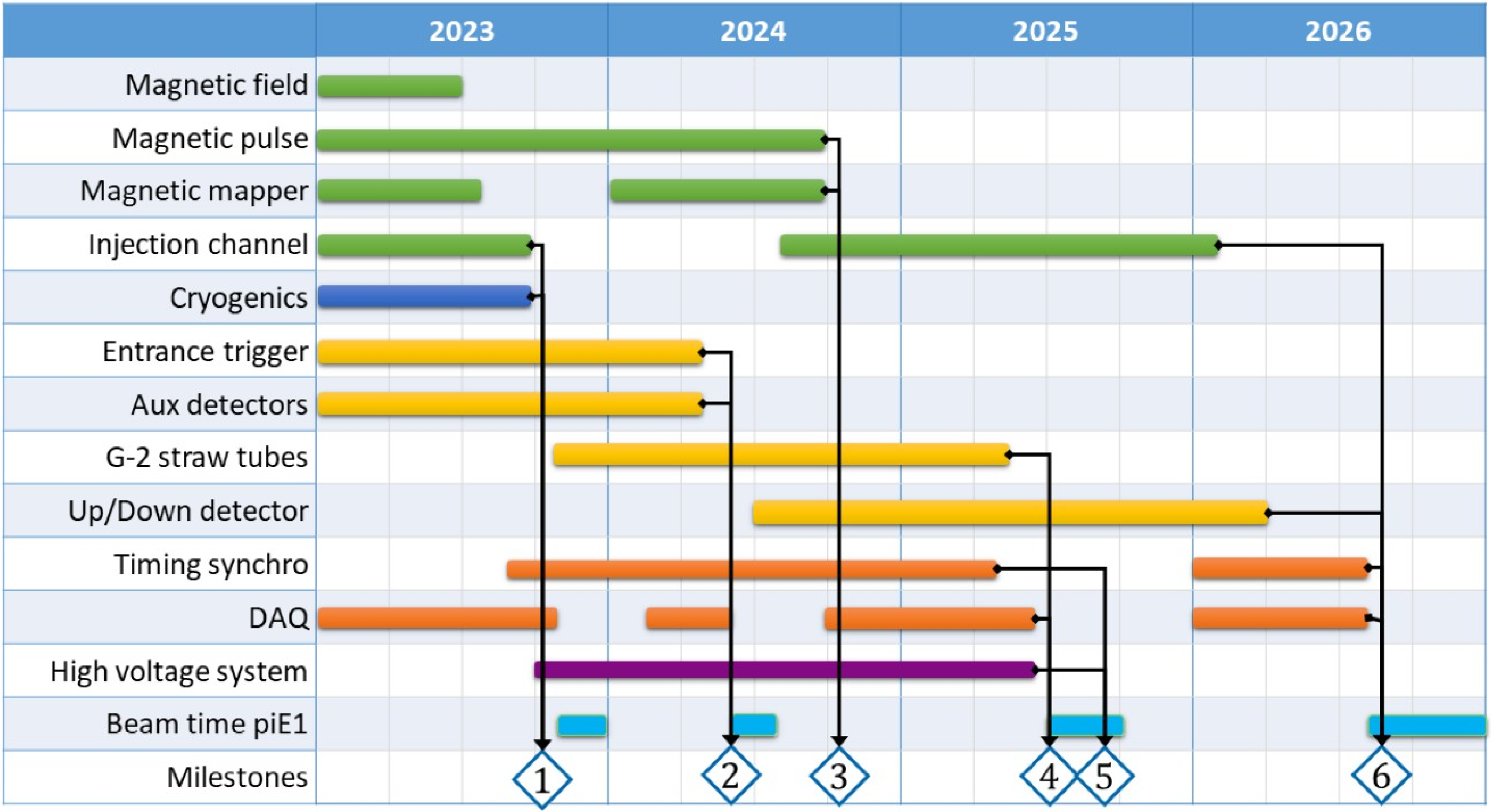
- thin scintillating fibers of 250 μm size coupled to silicon photomultipliers (SiPMs) that addresses the position and timing requirements for MIPs
- excellent tracking capacities for mip with a detector thickness below 0.4 %, a timing resolution better than 1 ns, and a spatial resolution of 1 mm
- the ribbons have a parallelepipedal shape (green elements) with photosensors at both ends

The Precursor Experiment Simulation



Details in talk by **A. Doinaki** in next session

Schedule


2023
2024
2025
2026
Magnetic field
Magnetic pulse
Magnetic mapper
Injection channel
Cryogenics
Entrance trigger
Aux detectors
G-2 straw tubes
Up/Down detector
Timing synchro
DAQ
High voltage system
Beam time piE1
Milestones
1
2
3
4
5
6