PAUL SCHERRER INSTITUT

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Search for a muon EDM

Muon4Future, Venice, 05/30/23

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

FNSNF
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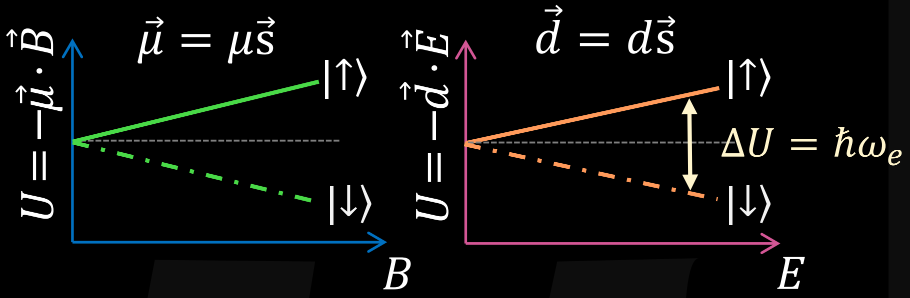
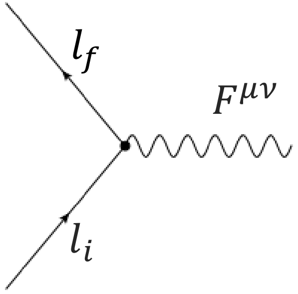
CP violation & edm



Lepton form factors and dipole moments



Effective Hamiltonian: $$\mathcal{H}_{\text{eff}} = c_R^{l_f l_i} \bar{l}_f \sigma_{\mu\nu} P_R l_i F^{\mu\nu} + \text{h.c.}$$

magnetic-dipole

Anapole - moment

$$\langle p' | J_\mu^{\text{EM}} | p \rangle = \bar{\Psi}(p') \left[F_1 \gamma_\mu + \frac{iF_2}{2M} \sigma_{\mu\nu} q^\nu + \frac{iF_3}{2M} \sigma_{\mu\nu} \gamma_5 q^\nu + \frac{F_4}{M^2} (q^2 \gamma_\mu - \gamma^\mu q_\mu q_\mu) \right] \Psi(p)$$

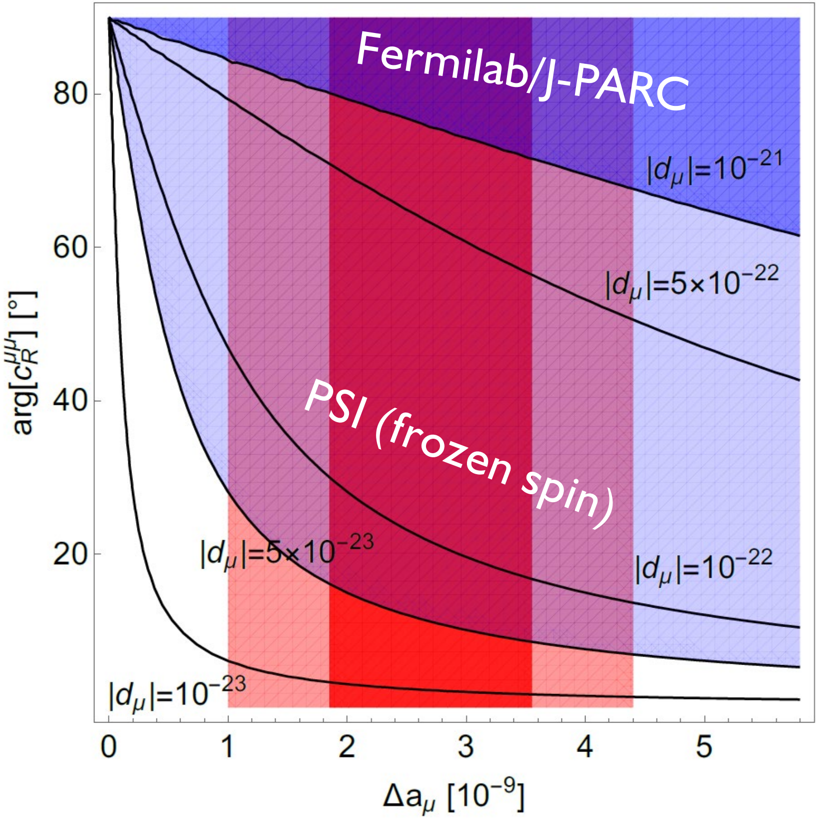
charge

electric-dipole

$$\delta F_2 = a_{l_i} = -\frac{2m_{l_i}}{e} \left(c_R^{l_i l_i} + c_R^{l_i l_i *} \right) = -\frac{4m_{l_i}}{e} \text{Re } c_R^{l_i l_i}$$

$$F_3 = d_{l_i} = i \left(c_R^{l_i l_i} - c_R^{l_i l_i *} \right) = -2\text{Im } c_R^{l_i l_i}$$

General limits on μEDM



- MFV: $\left|d_{\mu\leftarrow e}^{\mathrm{MFV}}\right| < 8.5\times 10^{-28} e\mathrm{cm}$
- Contribution only starts at the 3-loop level*

$$\left|d_{\mu\leftarrow e}\right| < 4\times 10^{-20}\ e\mathrm{cm}$$

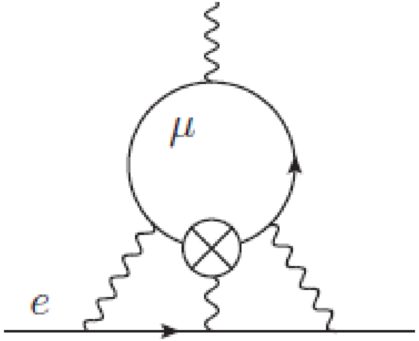
- Y. Ema et al., PRL **128**, 131801 (2022)

$$\left|d_\mu\left({}^{199}\mathrm{Hg}\right)\right| < 6\times 10^{-20}\ e\mathrm{cm}$$

$$\left|d_\mu(\mathrm{ThO})\right| < 2\times 10^{-20}\ e\mathrm{cm}$$

- Bennett et al., PRD80, 052008 (2009)

$$\left|d_\mu\right| < 1.5\times 10^{-19}\ e\mathrm{cm}$$

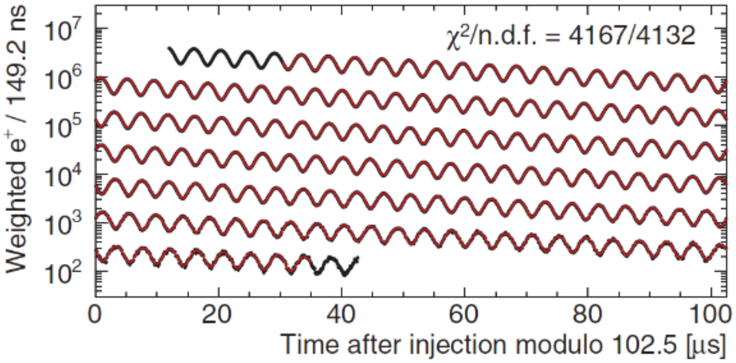


*A.Crivellin, M. Hoferichter, PSW PRD 98, 113002 (2018)

Muon dipole moments and frequencies

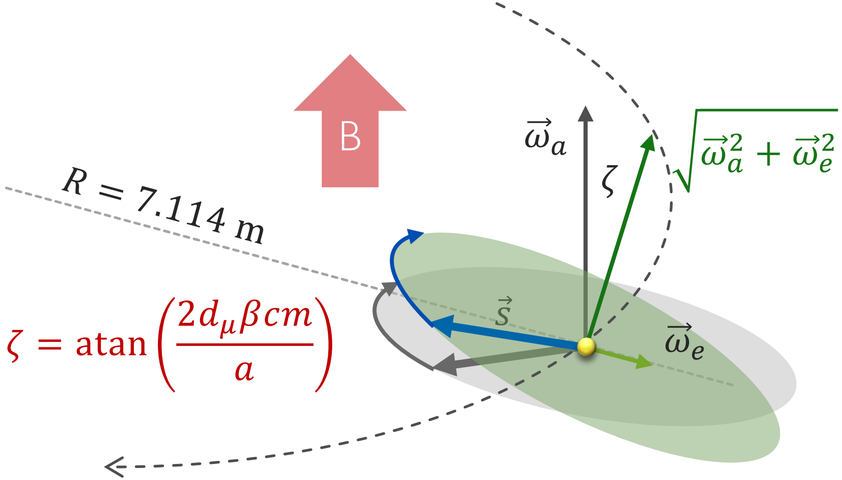
$$\vec{\omega} = \vec{\omega}_L - \vec{\omega}_c = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

g-2 term ω_a



FNAL* & JPARC**: $\sigma(d_\mu) \approx 10^{-21} ecm$

$$\zeta = \text{atan}\left(\frac{2 d_\mu \beta c m}{a}\right)$$



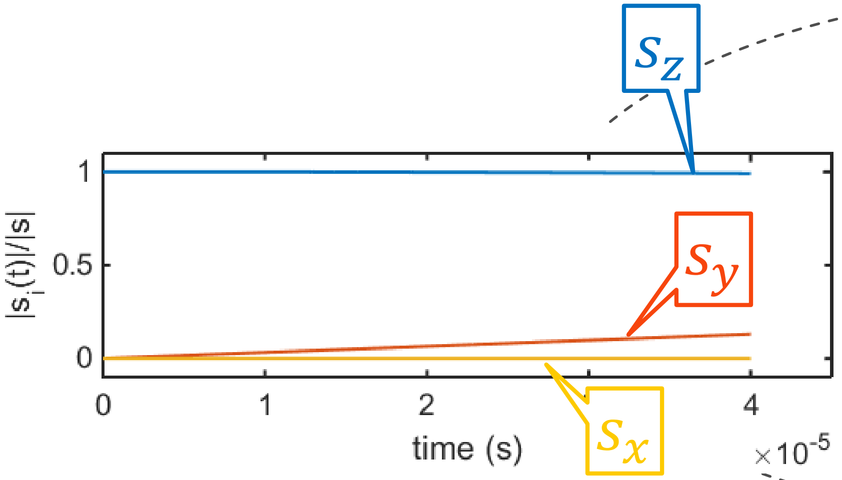
Muon dipole moments –freezing the spin at PSI

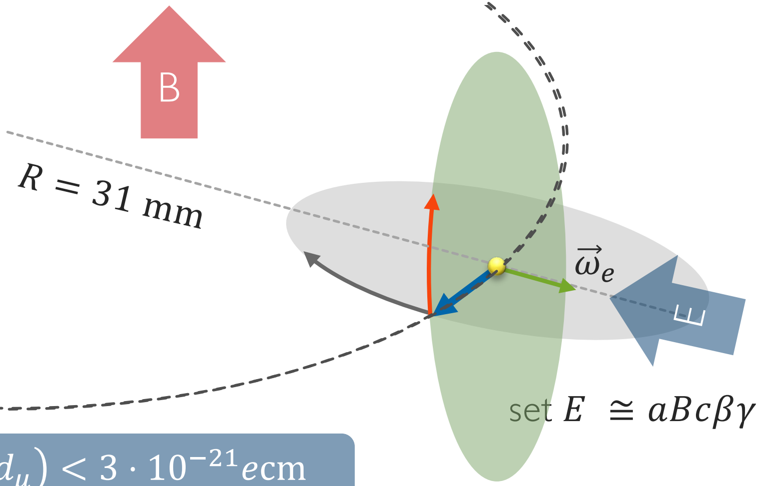
$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\Bigg]$$

g-2 term ω_a

EDM term ω_e

Frozen-spin potential at PSI: $\sigma(d_\mu) < 6 \cdot 10^{-23} ecm$



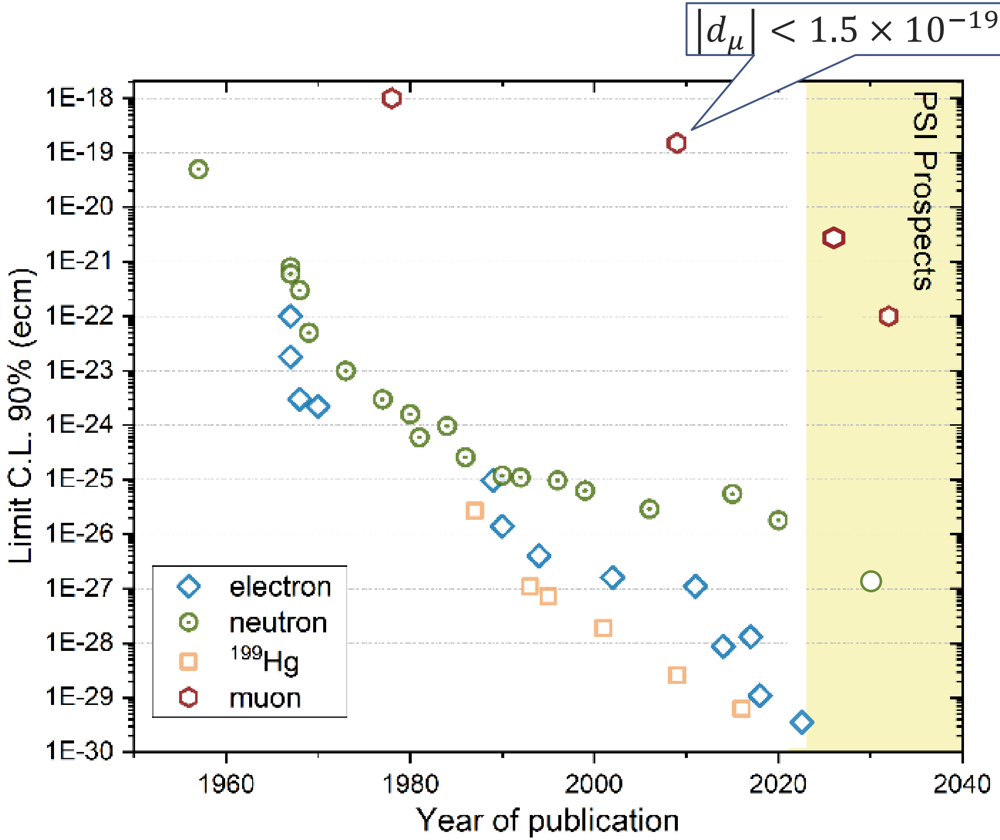


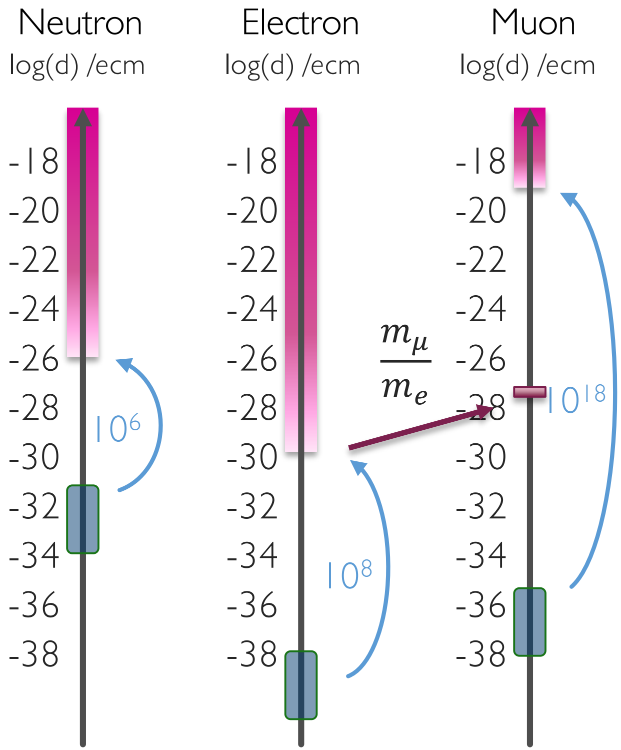
set $E \cong aBc\beta\gamma^2$

Phase I: $\sigma(d_\mu) < 3 \cdot 10^{-21} ecm$

[*Farley et al,, PRL93 042001 (2004)] ,

A not so brief history of EDM searches





*Bennett et al., PRD80(2009)052008

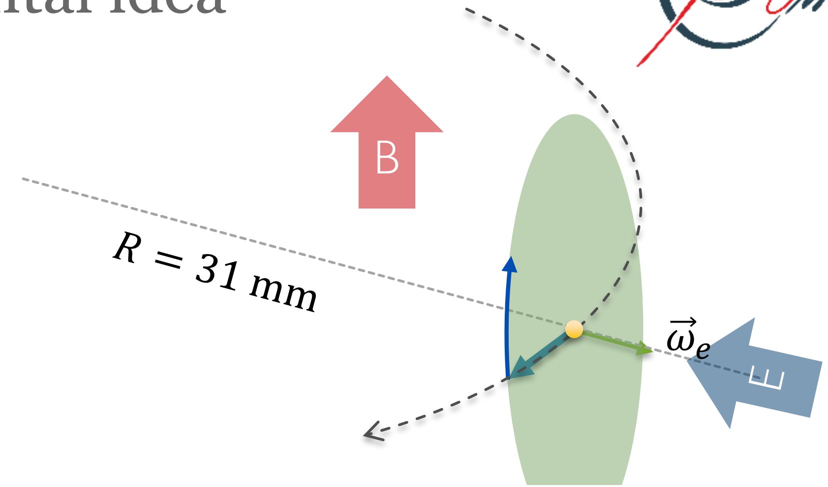
** Abel et al., PRL124(2020)081803

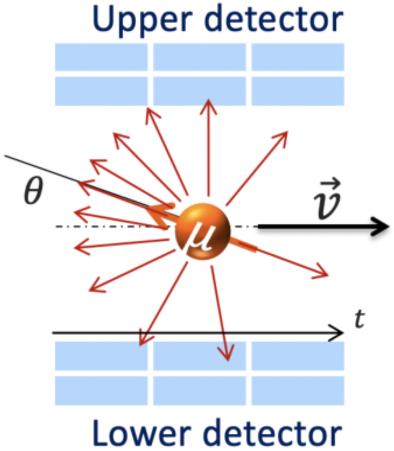
The general experimental idea

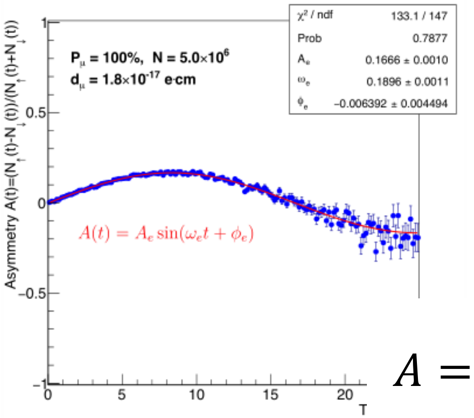
- If the EDM $\neq 0$, then there will be a vertical precession out of the plane of the orbit
  - An asymmetry increasing with time will be observed recording decay positrons

- If the EDM $= 0$, then the spin should always be parallel to the momentum
  asymmetry should be zero

- **Some asymmetry could still be observed due to systematic effects**

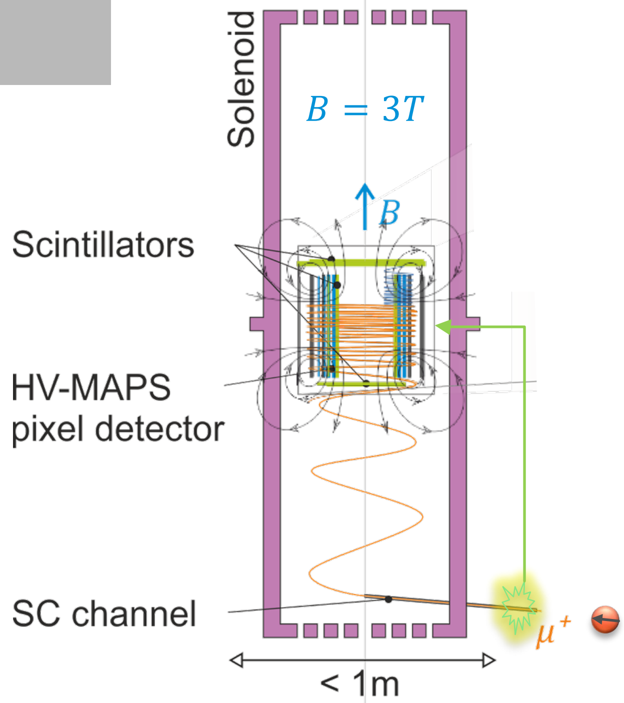


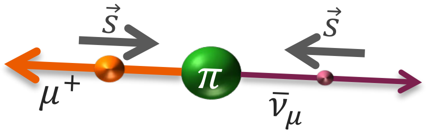




$$A = \frac{N_u - N_d}{N_u + N_d}$$

Search for a muon EDM using the frozen-spin technique with longitudinal injection

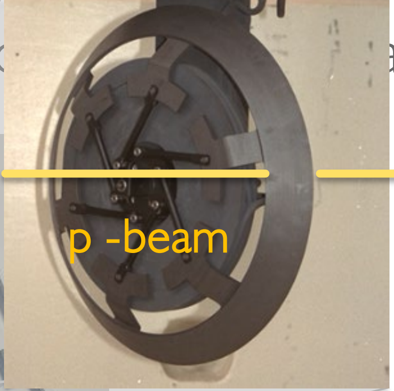


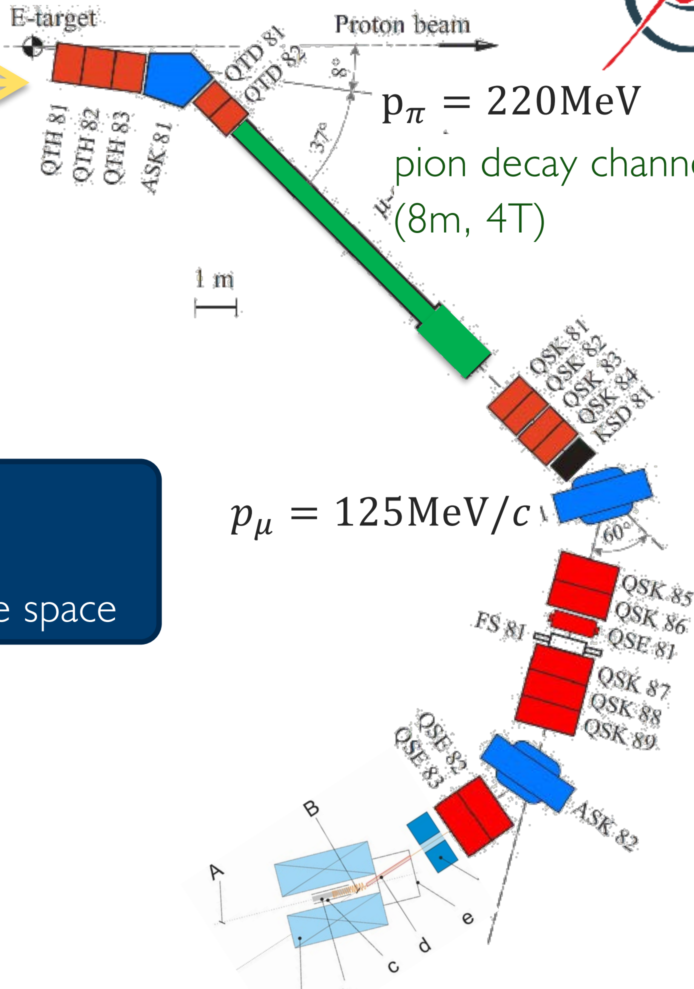


μ^+ @ $125\text{MeV}/c$ or $28\text{MeV}/c$

- μ^+ from **Pion-decay** $\rightarrow$ high polarization $p \approx 95\%$
- Injection through **superconducting channel**
- **Fast** scintillator **triggers** pulse
- Magnetic **pulse stops** longitudinal motion of μ^+
- Weakly focusing field for **storage**
- **Thin electrodes** provide electric field for **frozen spin**
- Pixelated detectors for e^+- **tracking**

A searc … at PSI





$p_\pi = 220\text{MeV}$

pion decay channel
(8m, 4T)

$p_\mu = 125\text{MeV}/c$

μ-beam:

- $10^8 \mu^+/s$
- Large phase space

A phased approached

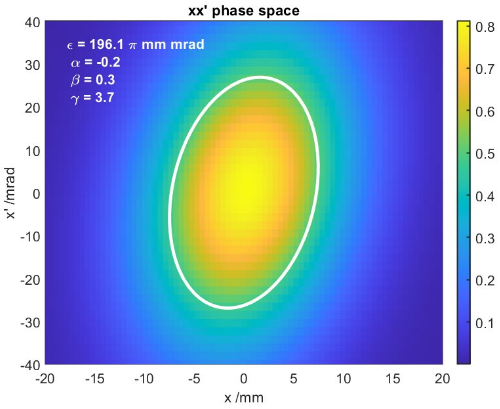
Phase I (small solenoid, surface muons)

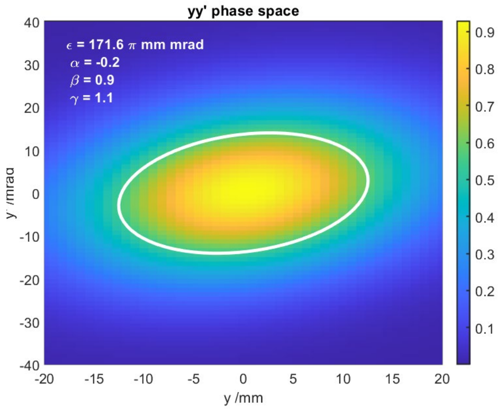
- Existing solenoid at PSI, max 5T
- Bore diameters 200mm
- Field was measured in 2022 (found suitable for injection)

Phase 2 (dedicated magnet muon momentum $\geq 125\mathrm{MeV}/c$)

- Large bore (up to 900 mm diameter)
- High Temporal field stability (10ppb/h)
- Excellent spatial field uniformity (< 1 ppb/mm)

Injection and statistical sensitivity





xx': $\epsilon = 196\pi$mm mrad

yy': $\epsilon = 171\,\pi$mm mrad

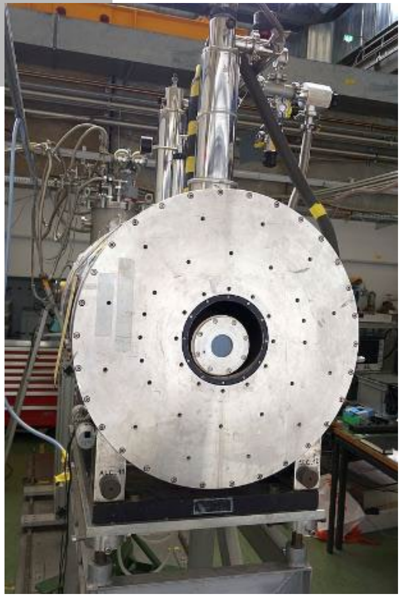
- Large phase space at exit of beam collimated by passage through a collimation channel
- Due to adiabatic magnetic collimation large part of transmitted μ^+ are reflected.
- Storage efficiency $\sim 5 \times 10^{-4}$

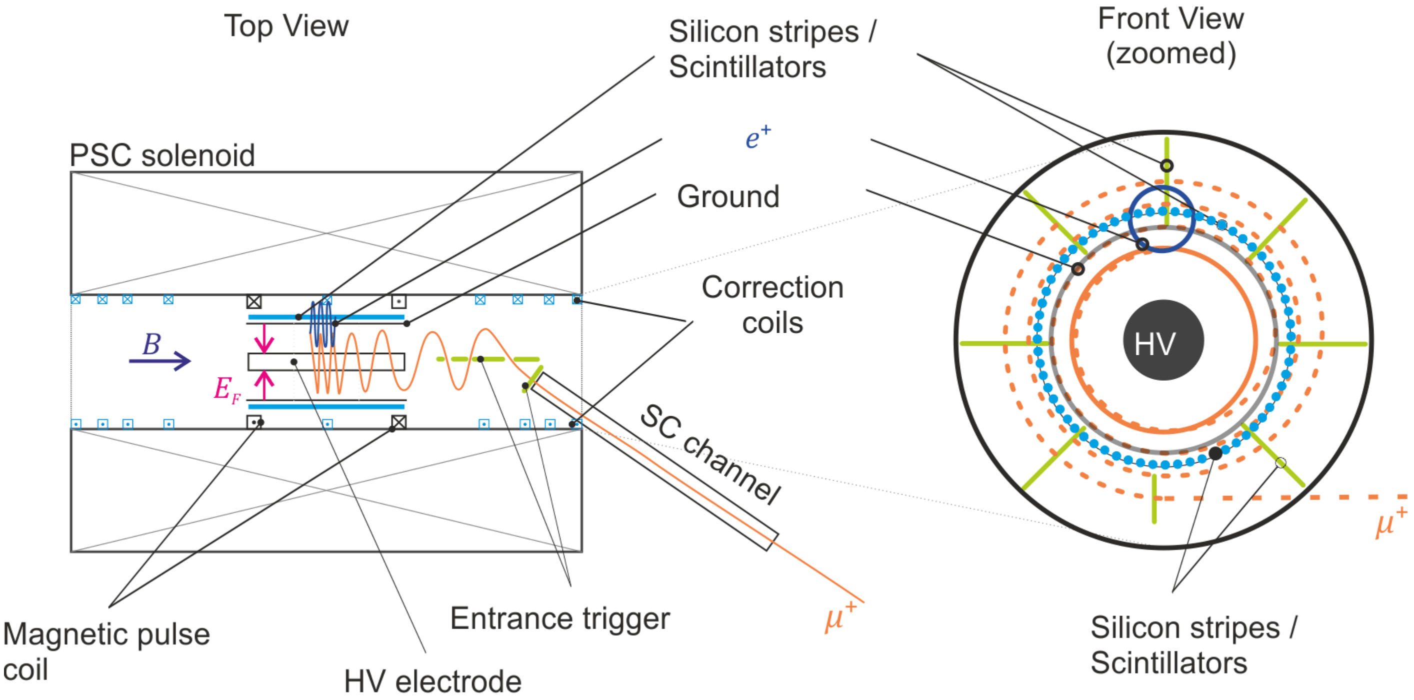
$$\sigma(d_\mu) = \frac{\hbar \gamma a_\mu}{2pE_f\sqrt{N}\,\tau_\mu\,\alpha}$$

	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)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

The muEDM phase I on piE1

Test bed and frozen spin demonstrator





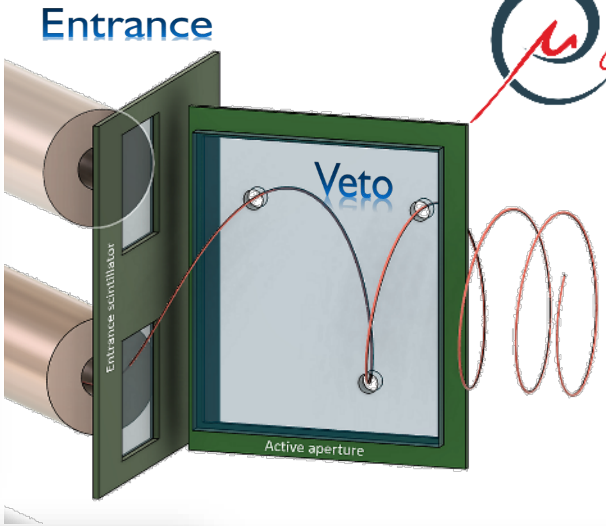
muEDM measurement $< 3 \cdot 10^{-21} ecm$

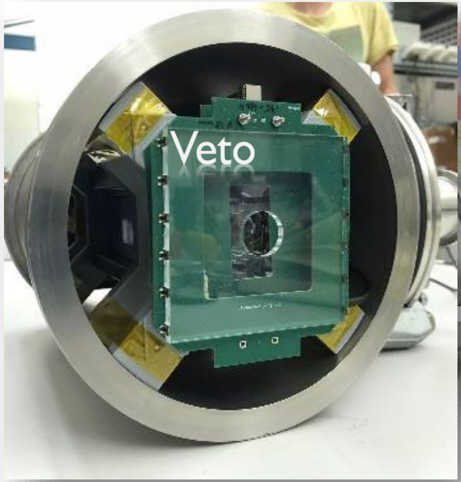
Muon entrance trigger

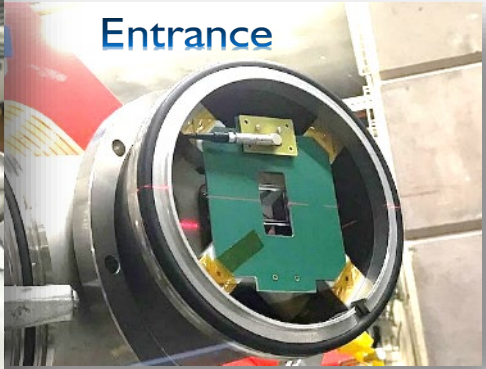
- Magnetic pulse needs to be triggered by incident muon
- Only about 1% of muons passing through the collimation channel are within the acceptance phase space
- Scattering in scintillators increase beam divergence

↓

- Combine thin ($\leq 100\mu m$) entrance scintillator with an active aperture as veto

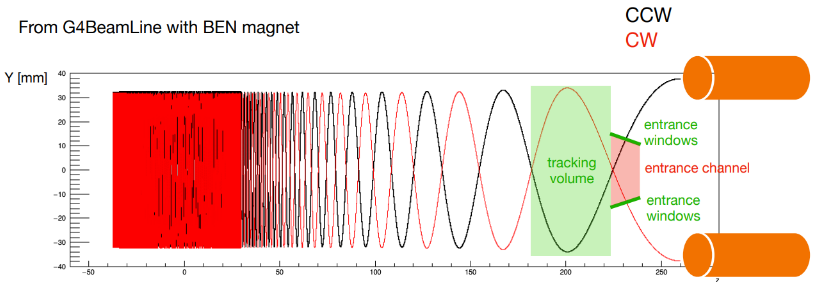


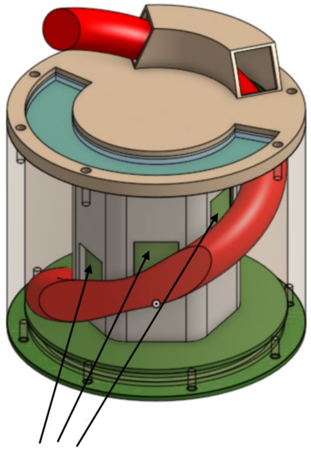




Muon Tracking Detectors

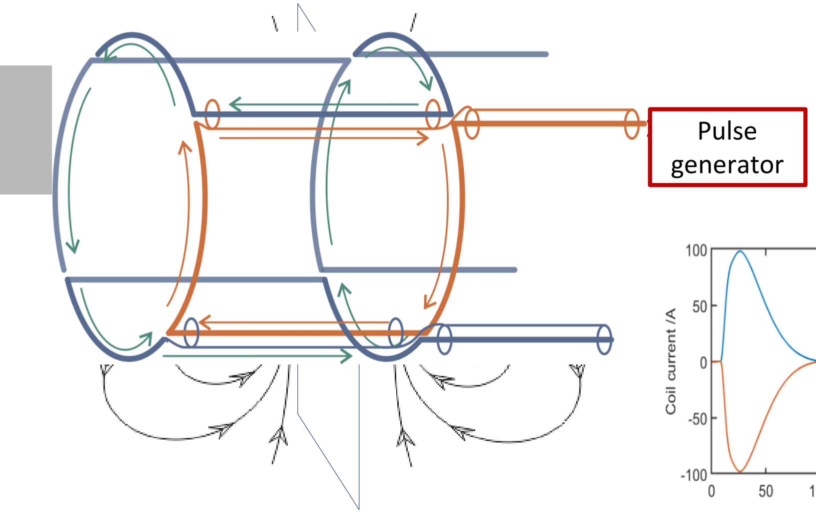
- Need to characterize muon trajectory before EDM measurement
- Requires ~ mrad angular and ~0.1% momentum resolution
- Gaseous TPC with 2 geometries possible: longitudinal drift (for momentum), radial drift (for angle).
- Design satisfying constraints with sufficient phase-space acceptance possible 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

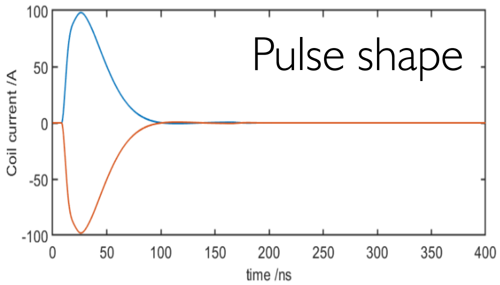


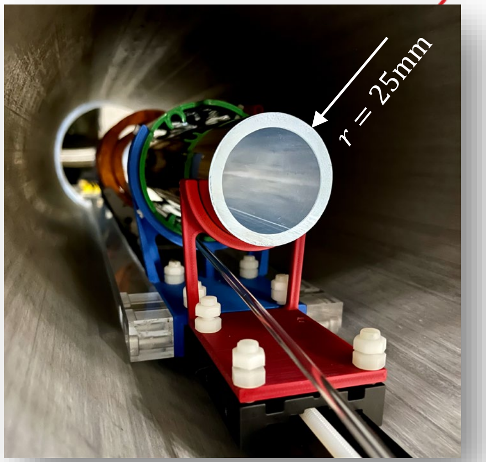


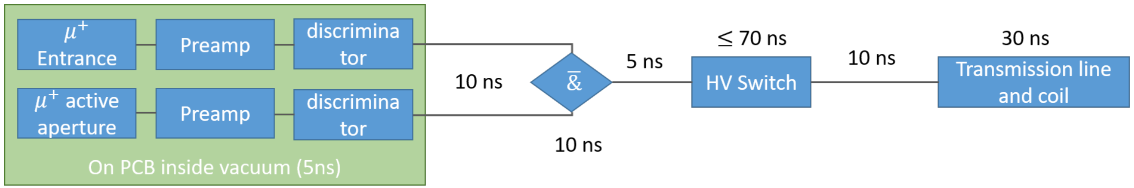
(courtesy F. Renga)

Radial magnetic field pulse to kick muons









- PS delay input → output $\delta t < 60$ ns
- Pulse FWHM ~ 40ns
- Peak current per coil ~170 A
- Includes damping effect (factor 2) by Eddy currents
- Suppression of oscillation in tail < 1 A (corresponds to $B_{osc} < 5\mu T$)

Positron detection – figure of merit

Detection of g-2 precession ω_a

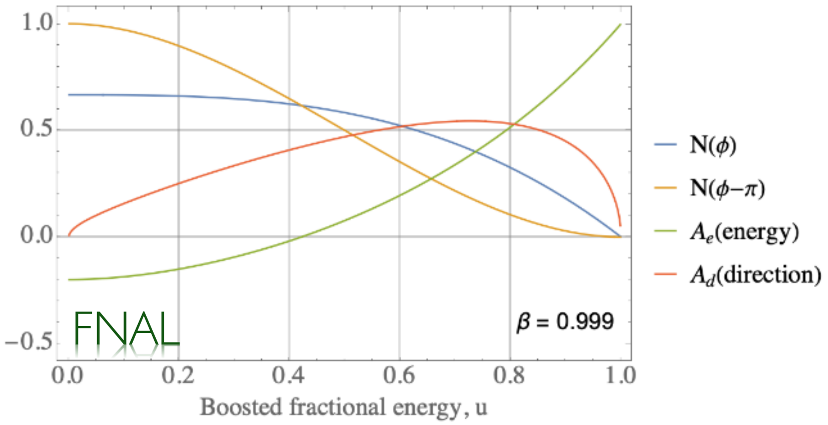
- Measurement of mean magnetic field $\langle B \rangle$
- Measure $\omega_a(E)$ to tune electric field to frozen-spin condition

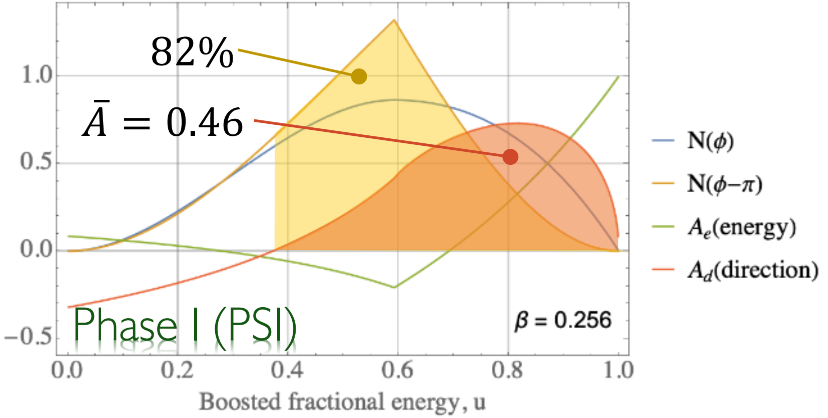
Requires momentum resolution

Detection of EDM polarization

- Measurement of Asymmetry as function of time $A(t)$

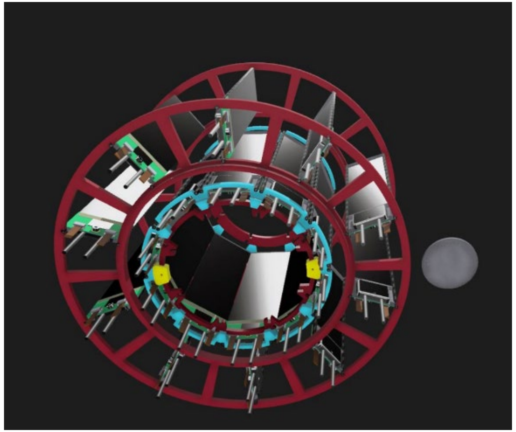
Requires spatial resolution along cylinder

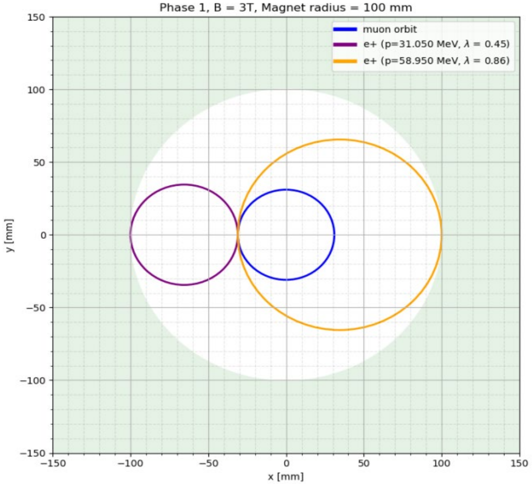


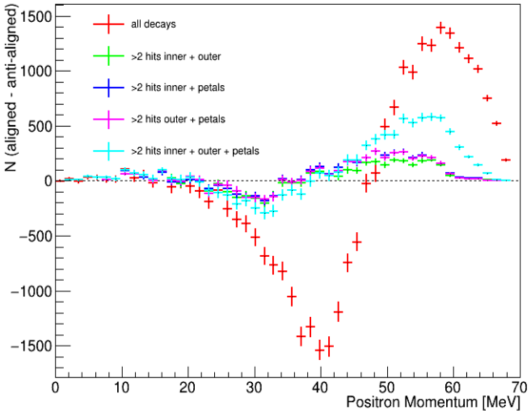


Positron Detection for g-2

- Measurement of g-2 to measure B-field and determine voltage for frozen spin condition
- For Phase I ($p = 28$MeV) maximum energy is $\sim$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





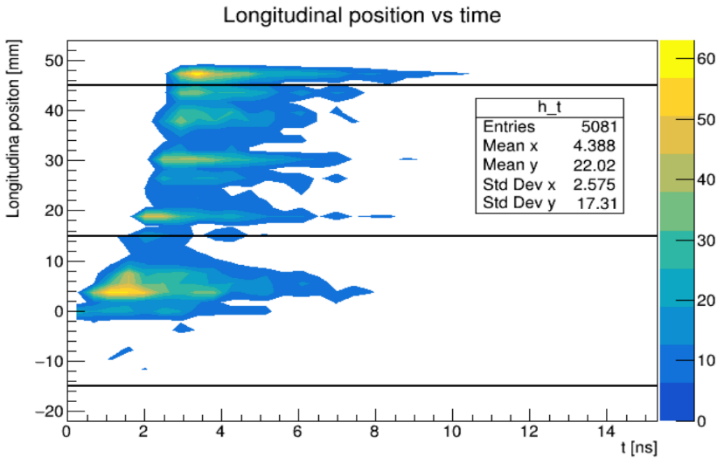


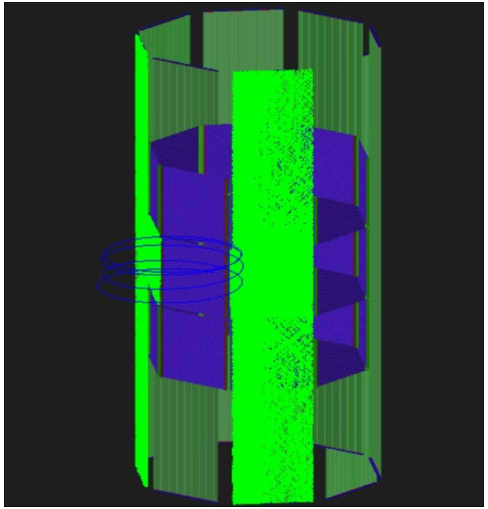
(courtesy J. Price)

Positron Detection for EDM

- For EDM signal, detect up-down asymmetry in photons

- Double barrel Scifi 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





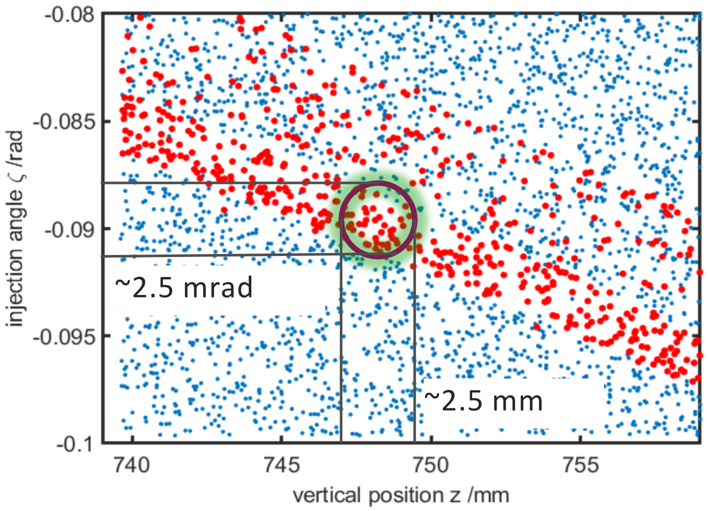
- Photon time and position (longitudinal info on internal barrel)
- Large number of readout channel a challenge
- Considering other possible geometries

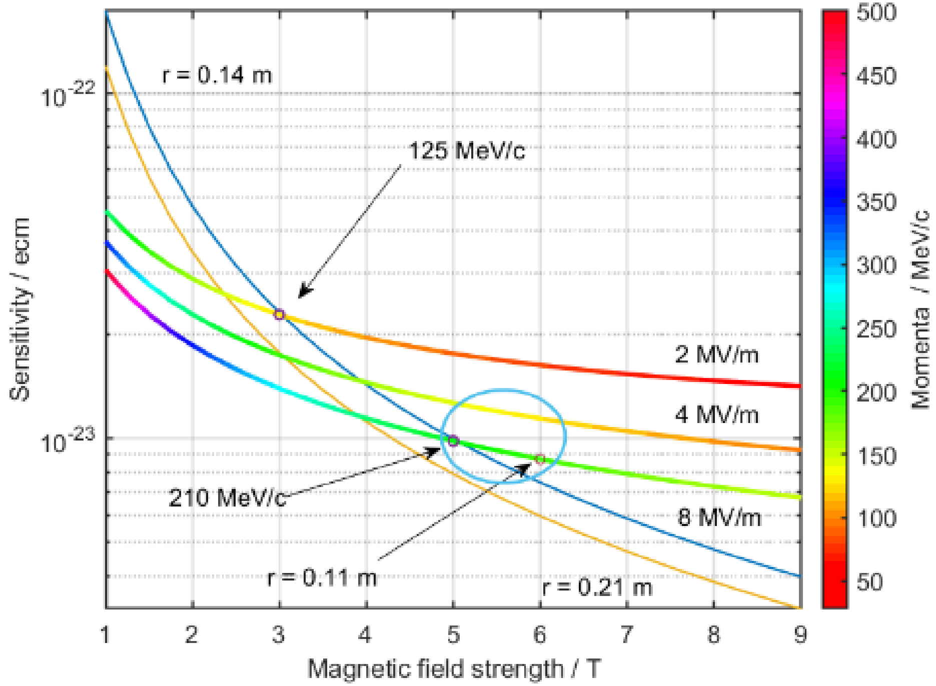
(courtesy B. Vitali)

muEDM/(g-2) needs in the future

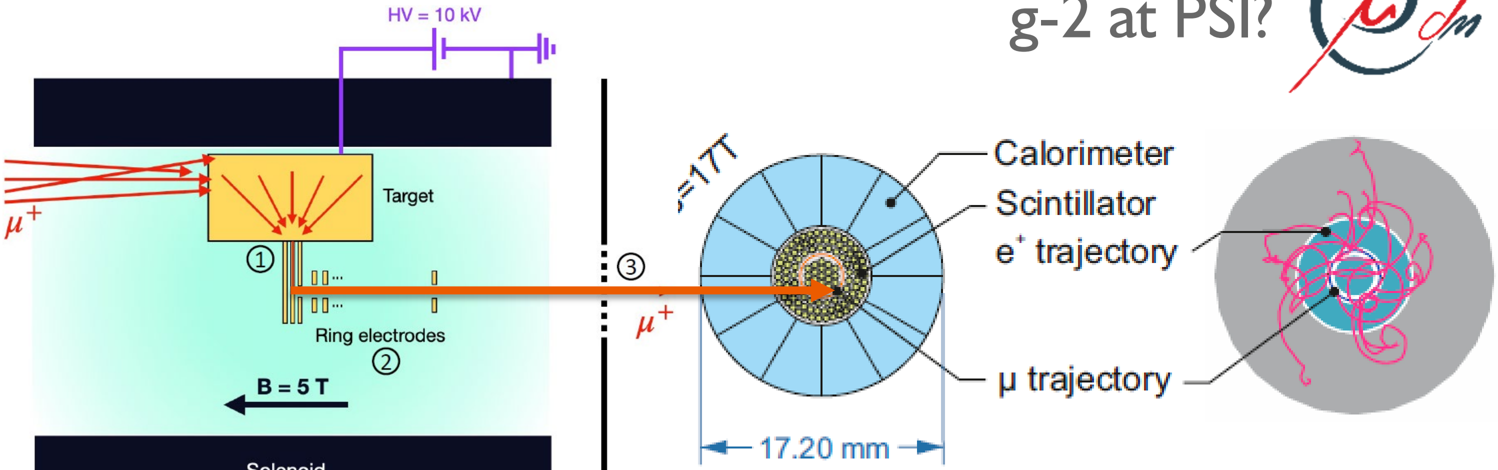
- Low emittance & high flux
  to inject all delivered muons
- "Muon on request"
  or pulsed beam
- The more muons the merrier

$$E \approx aBc\beta\gamma^2$$

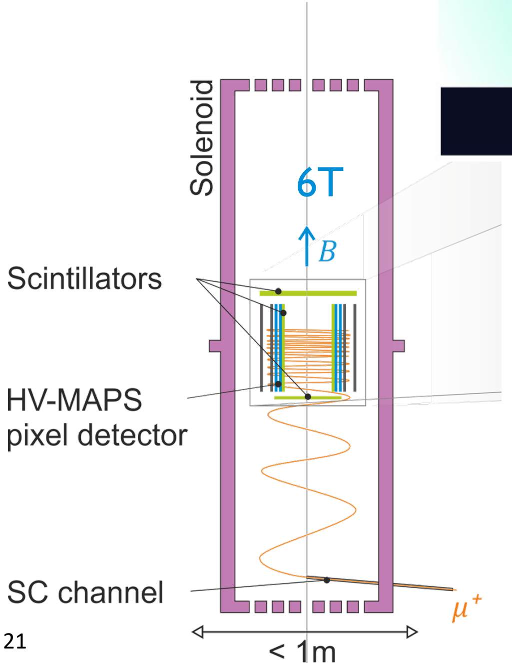




g-2 at PSI?



c.f. D. Taqqu



	Fermilab E989	J-PARC	AMMiED	TiAMMo
Muon momentum	30.9 GeV/c	300 MeV/c	125 MeV/c	14.6 MeV/c
Lorentz γ	29.3	3	1.56	1
Polarization	100%	50%	95%	95%
Magnetic field B	1.45 T	3 T	6 T	17 T
Focusing field	E-quadrupoles	weakly focusing (wf)	wf	wf
Cyclotron period	149 ns	7.4 ns	3.8 ns	0.4 ns
AMM precession period	4.37 µs	2.11 µs	1.05 µs	0.37 µs
Number of detected e^+	1.6×10^{11}	5.7×10^{11}	7×10^{12}	1.7×10^{12}
AMM precision (stat.)	0.1 ppm	0.45 ppm	0.1 ppm	0.08 ppm
AMM precision (sys.)	0.1 ppm	0.07 ppm	0.07 ppm	0.07 ppm

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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, **further improvement with pulsed beams possible (e.g. Fermilab FFA?)**

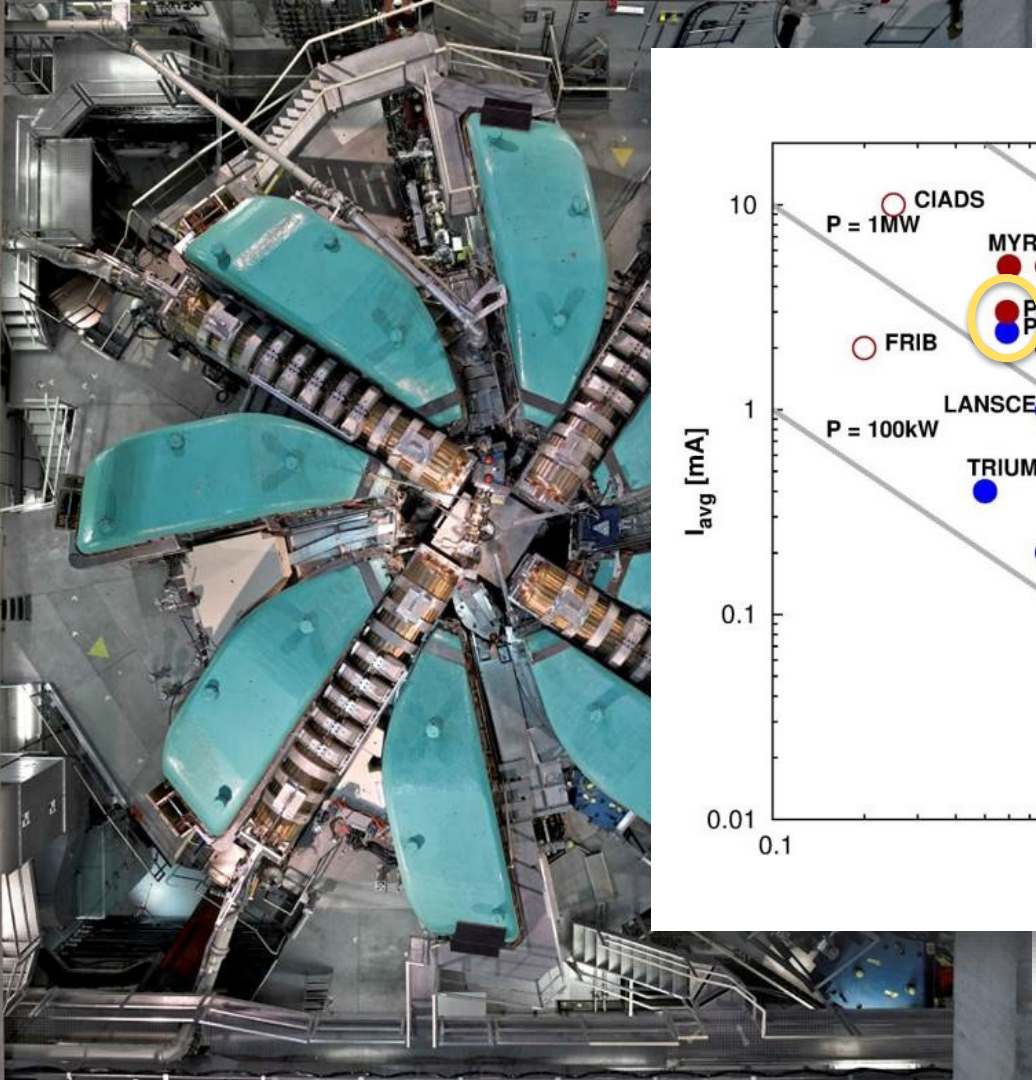
- The experiment will take place in two phases, where we will demonstrate the frozen-spin technique in phase I

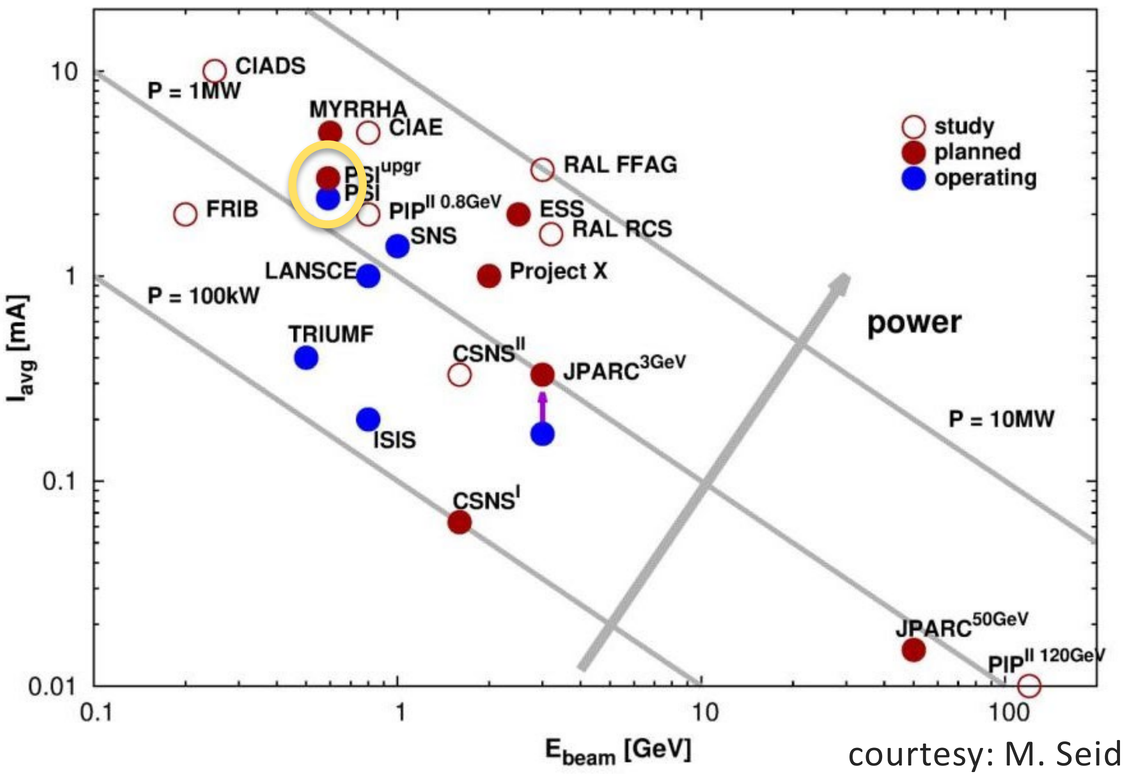
- Optimization of the design for Phase I underway using simulation studies:
  prototype building of important components
  Test beams demonstrating feasibility

- A tinny g-2 could profit from a re-accelerated low emittance cold muon source
- Muon multiplicity would require much higher efficiency for muCool

The Collaboration

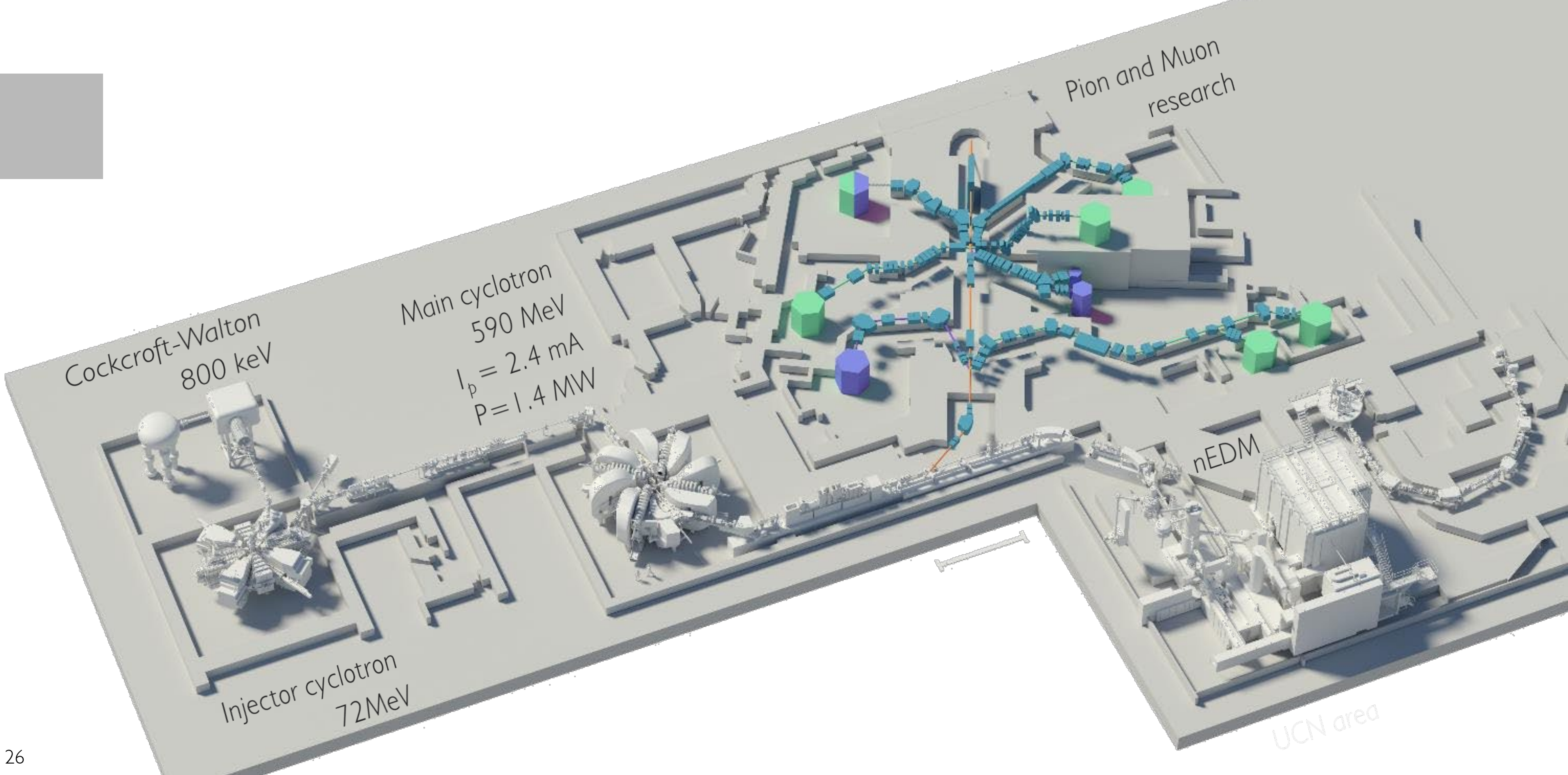
Backup





courtesy: M. Seidel

HIPA – High intensity proton accelerator

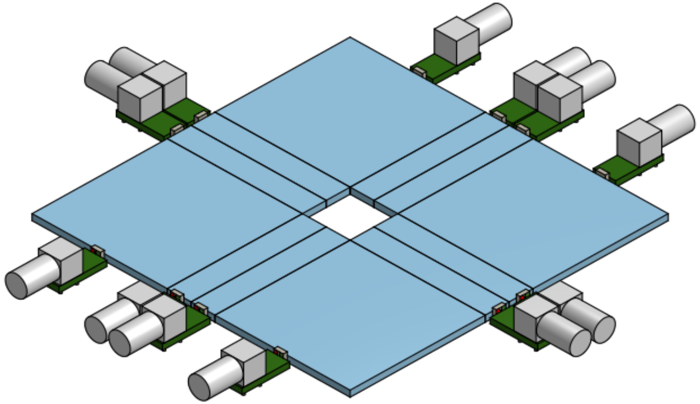


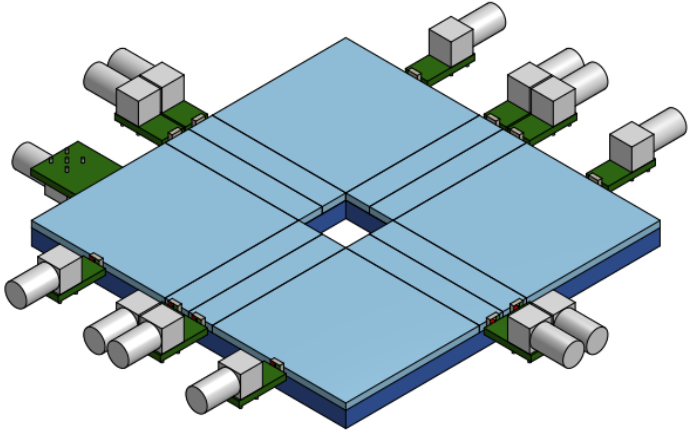
Muon Entrance Monitor

- 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)

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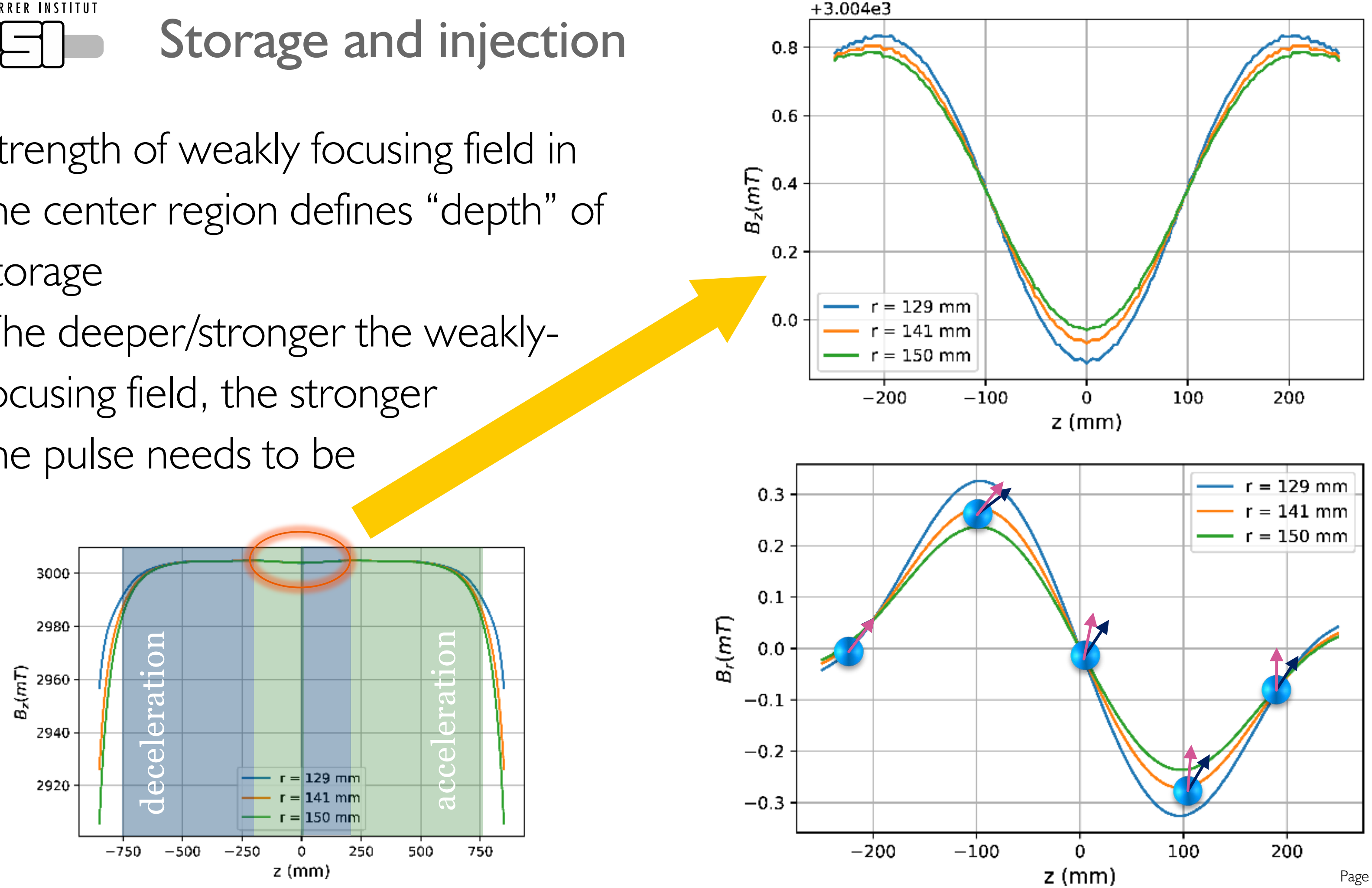
Storage and injection

- Strength of weakly focusing field in the center region defines “depth” of storage
- The deeper/stronger the weakly-focusing field, the stronger the pulse needs to be



Tuning the electric field to the frozen-spin condition

- Measure the g-2 frequency ω_a
- Two momentum bins

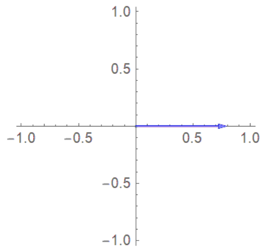
  $28\ \mathrm{MeV}/c < p_1 < 50\mathrm{MeV}/c$

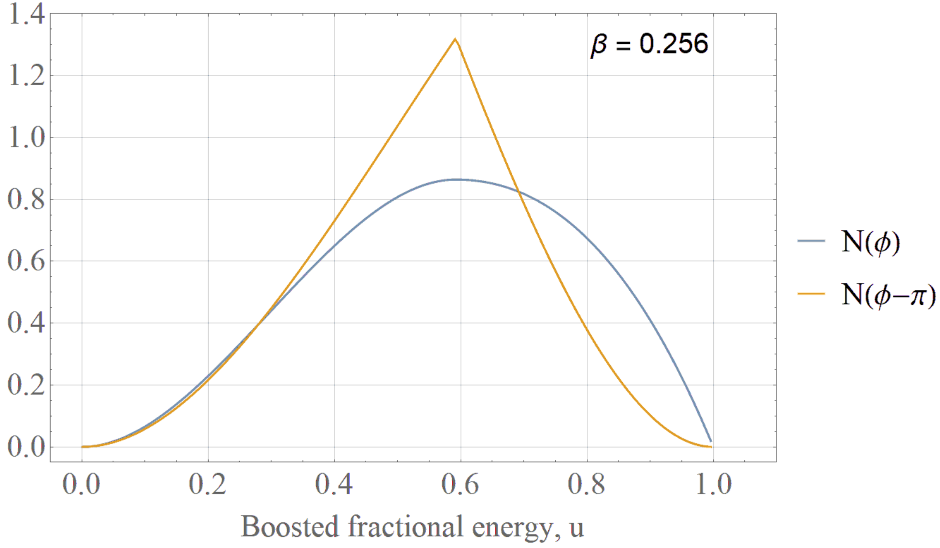
  $50\ \mathrm{MeV}/c < p_2$

- Change E field in the range

  $\pm E_{\mathrm{frozen}} \approx \pm 3\mathrm{kV/cm}$

- Extrapolate to E_{frozen} where $\omega_a = 0$

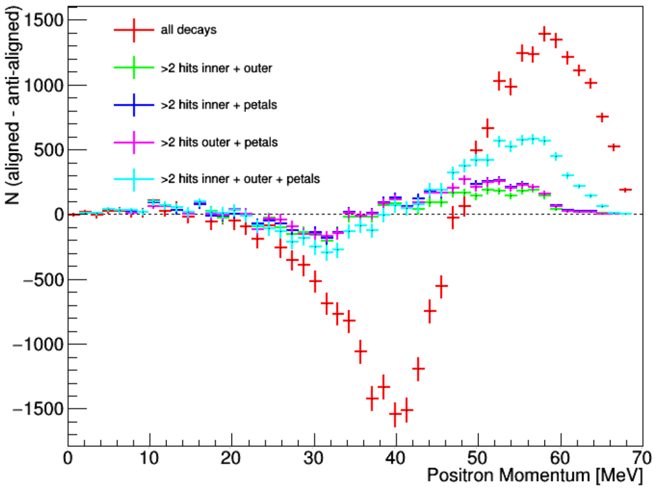


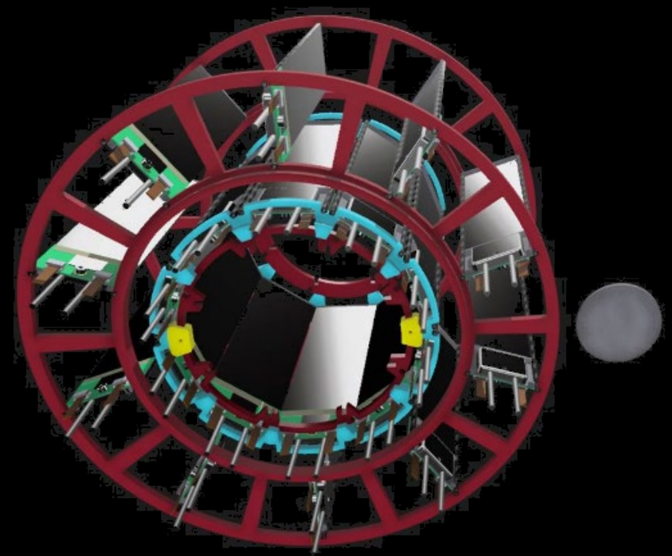


Silicon strip detector for g-2 detection

Silicon strip detector for g-2 detection

- Reconstruction of transverse positron momentum ($\Delta p \approx 5\mathrm{MeV/c}$)
- Timing $\Delta t \approx 2\mathrm{ns}$
- Spatial resolution $\approx 0.1\mathrm{mm}$ (lateral)



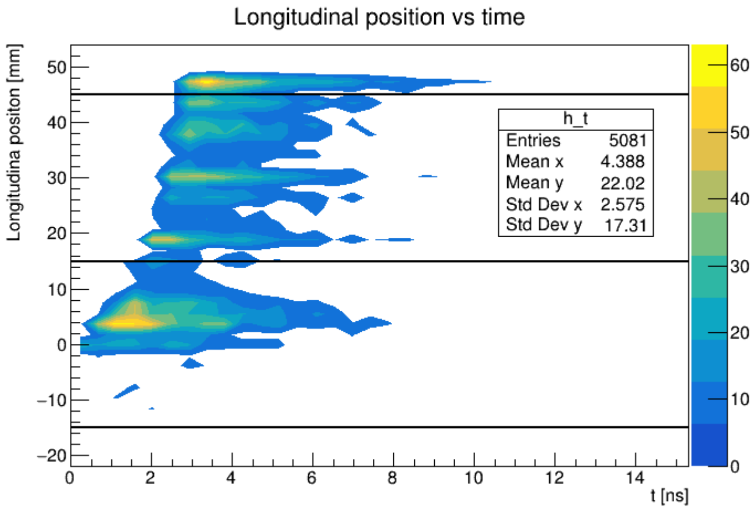


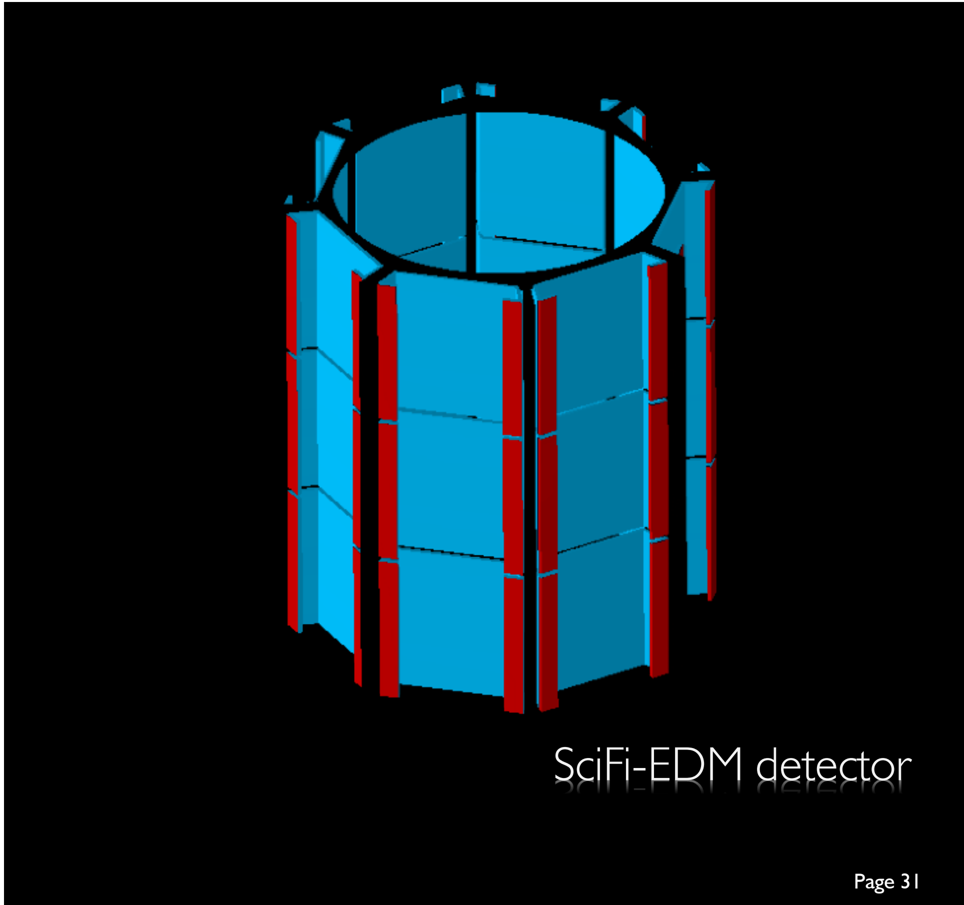
Si-Petal detector

Scintillating fiber detector for EDM-signal

Scintillating fiber detector for EDM asymmetry measurement and timing

- Horizontal fiber ribbons with $250\mu m$ pitch and $100\mu m$ resolution
- Timing resolution $< 2ns$
- Reconstruction of longitudinal momentum





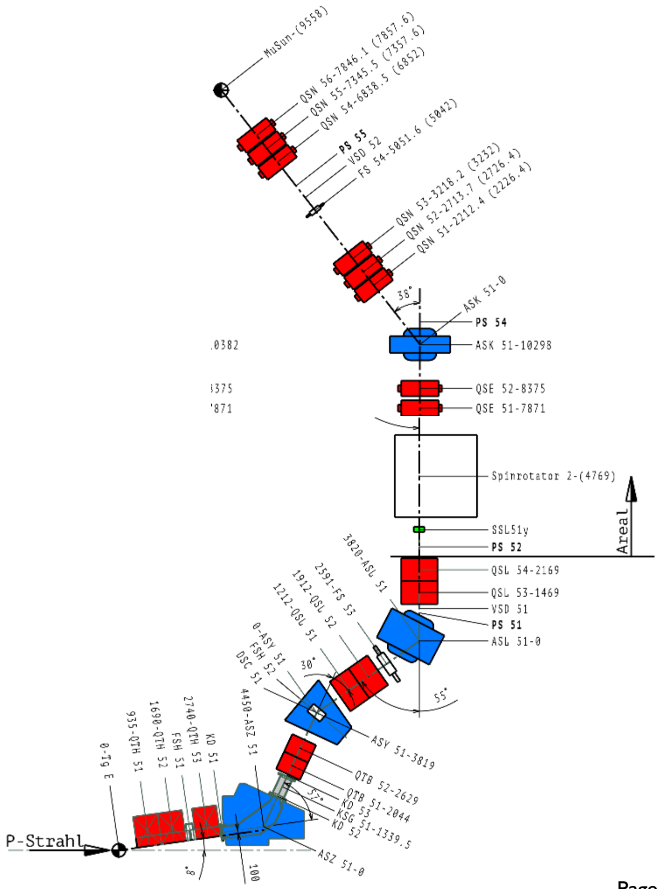
Surface muons for phase-I

Horizontal Emittance: $200\ \pi$mm mrad

Vertical Emittance: $170\ \pi$ mm mrad

- Beam rate about $4 \times 10^6\ s^{-1}$
- Acceptance phase space:
  - – High transmission through channel 3%
  - – Injection efficiency about 0.4%
  - – Expected μ^+ storage rate 2kHz
  - – Expected e^+ detection rate 0.5kHz

- Moderate E field 3kV/cm



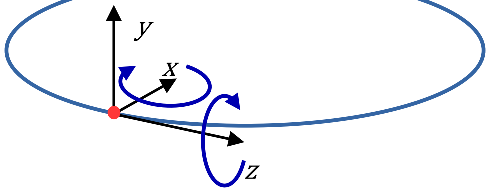
Systematic studies (example)

- Systematic effects: all effects that lead to a ***real*** or ***apparent*** precession of the spin around the radial axis that are not related to the EDM

- Major sources of systematic effects in the frozen spin technique:
  - Coupling of the magnetic moment with the EM fields of the experimental setup (***real***)
  - Early to late variation of detection efficiency of the EDM detectors (***apparent***)

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

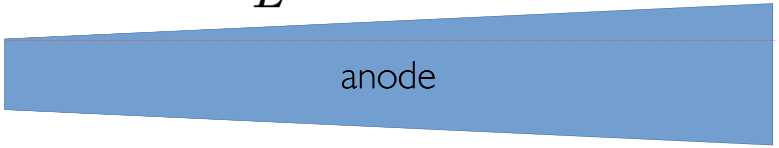
- **Rotations that could mimic the EDM:**
  - **Radial around x**
  - **Azimutal around z**



Sources of E_y field: conical central electrode

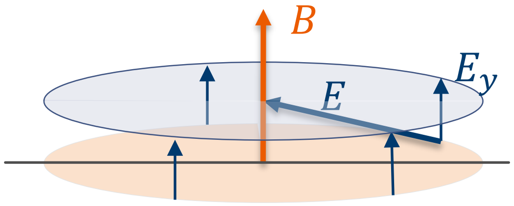
- None constant radius of cylindrical anode (cone)

$$E_y \approx E_f \frac{\Delta_R}{L} \approx E_f \alpha$$

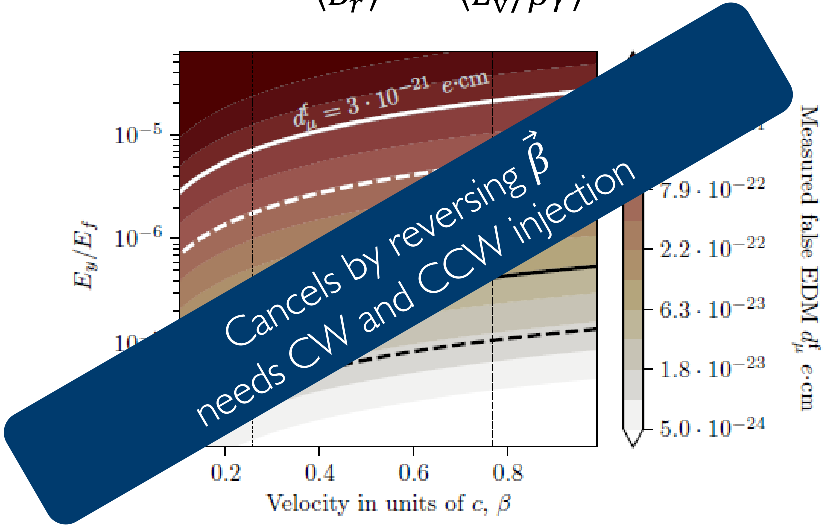


- Cylindricity on the order of 50 nm is measurable even on large samples and possible to machine

- Ground electrode made of thin foil more difficult to keep deviations from cylindricity below $30\mu m$

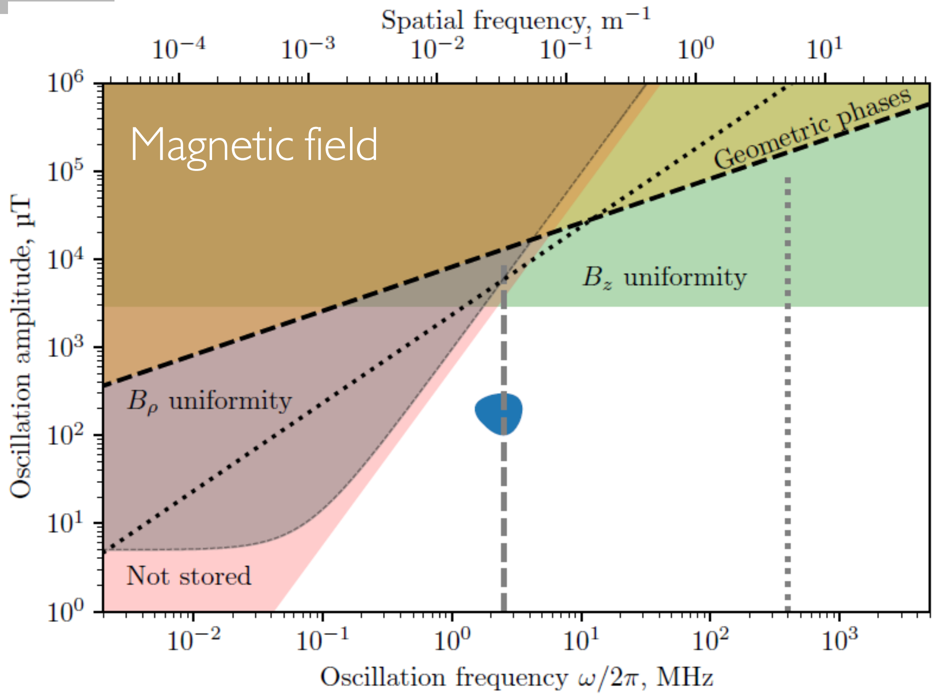


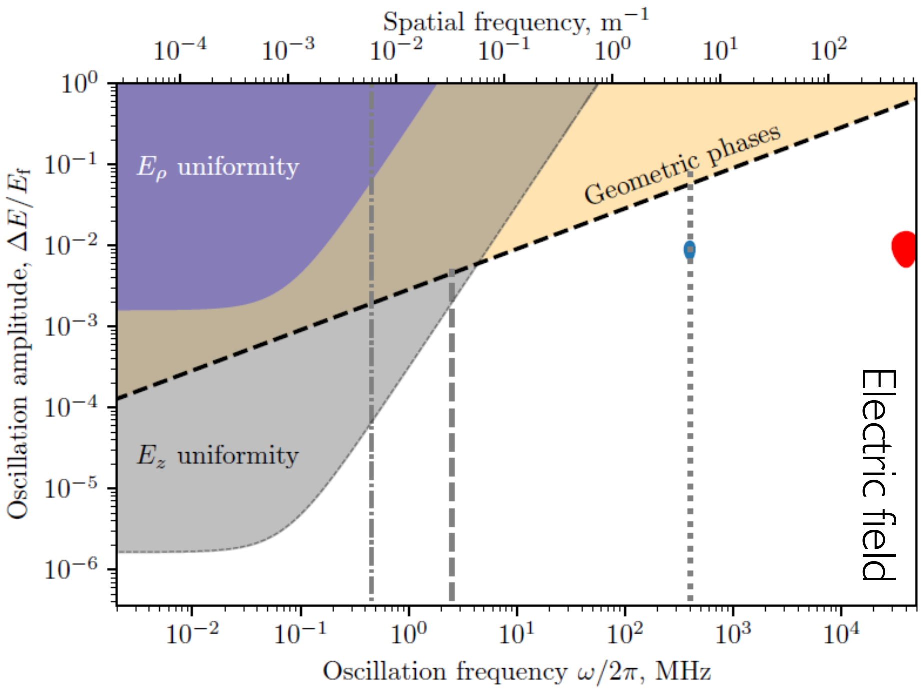
Will move orbit out of central plane until:
$$\langle B_r^* \rangle = -\langle E_v / \beta\gamma \rangle$$



Geometric phases, and non-uniformities

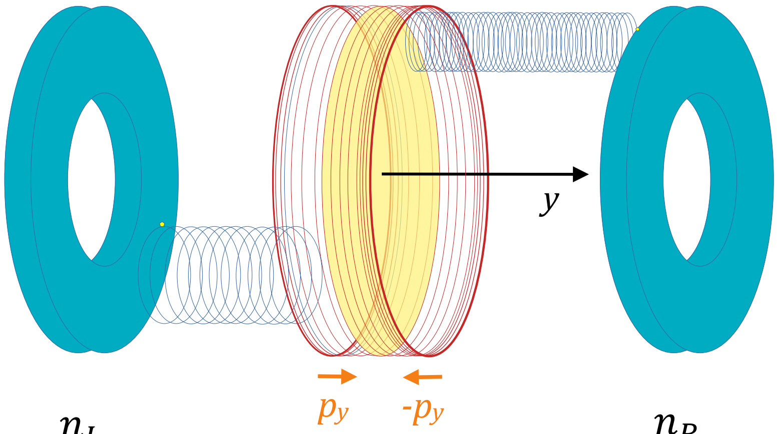
$$\frac{1}{4}\frac{\Omega_x\Omega_y}{\omega_x\omega_y}\left[\frac{\omega_x-\omega_y}{\omega_x+\omega_y}\cos((\omega_x+\omega_y)t+\beta_0)-\frac{\omega_x+\omega_y}{\omega_x-\omega_y}\cos((\omega_y-\omega_x)t+\beta_0)\right] \Rightarrow -\frac{1}{2\omega}\Omega_x\Omega_y t\sin(\beta_0)$$





Detection efficiency asymmetry

- The EDM will be deduced from the accumulation of asymmetry between the upstream and downstream detectors that increases with time
- Static differences in the detection efficiency of one detector compared to the other is not a problem
- Change of the detection efficiency with time is a problem as it will introduce time dependent asymmetry



Constraints on the total detection efficiency

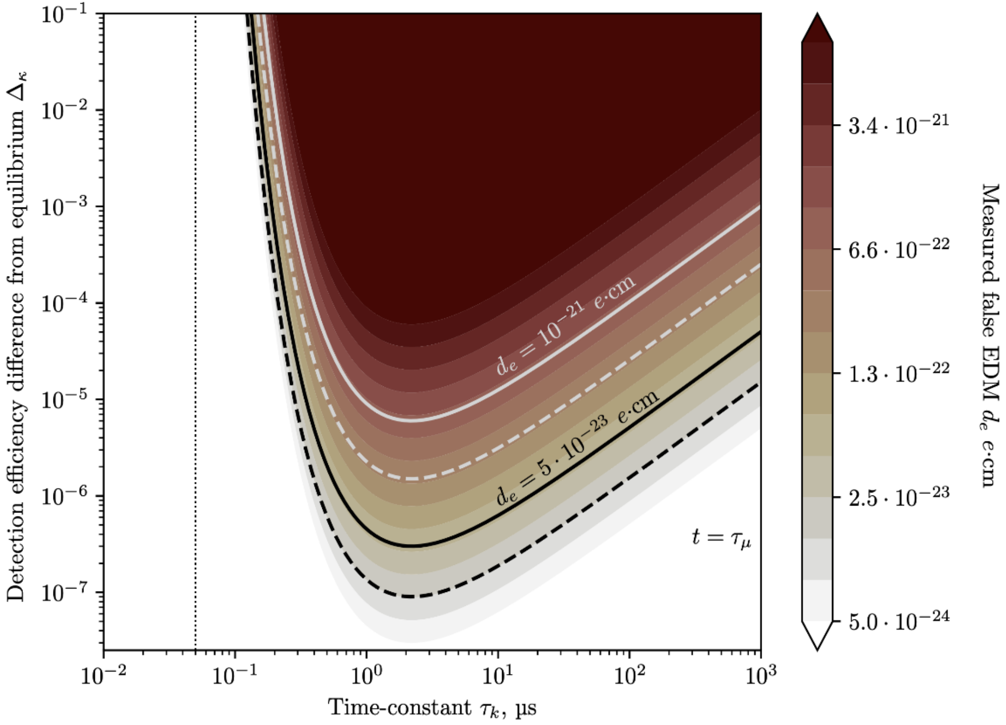
- Assumption: Change of detection efficiency triggered by pulse, exponential decay

- Detection efficiency of up and downstream detectors:

$$\kappa_u = \kappa_{u0} - \Delta_\kappa e^{-t/\tau_k},$$
$$\kappa_d = \kappa_{d0} + \Delta_\kappa e^{-t/\tau_k},$$

- Change in measured asymmetry with time:

$$\dot{A}_m = \frac{2}{\tau_k}\Delta_\kappa e^{-t/\tau_k}$$



Systematic study - overview

- Systematic effects are studied using analytic expressions
- Comparison with GEANT4 spin tracking Monte Carlo for verification
- Deduce specifications for experiment

Next steps:
- Parametrization of magnetic-field non-uniformity
- Deduce magnetic-field requirements

Systematic effect	Constraints	Phase I	
		Expected value	Syst. ($\times 10^{-21}$ e·cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ µm	0.75
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$
Net current flowing muon orbit area	Wiring of electronics inside the orbit	< 10 mA	$< 10^{-2}$
Longitudinal B-field uniformity	Solenoid alignment	< 3 mT	-
Resonant geometrical phase accumulation	Misalignment of central axes	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}
TOTAL			1.1

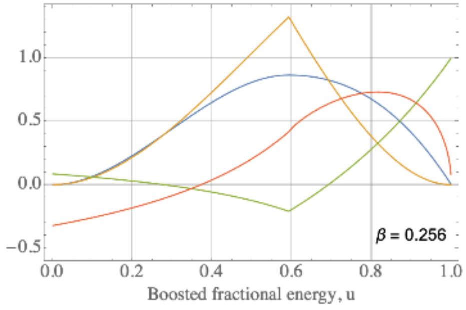
Going from phase I to phase II

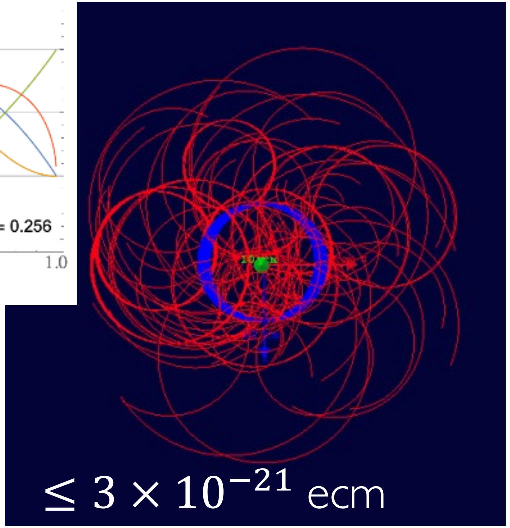
Phase I

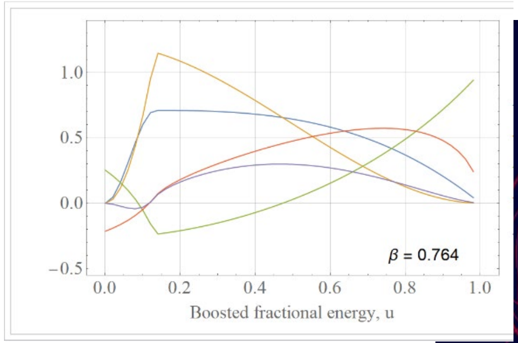
- B-Field 3T
- Momentum 28 MeV/c
- Muon radius 31mm
- Most positrons outside

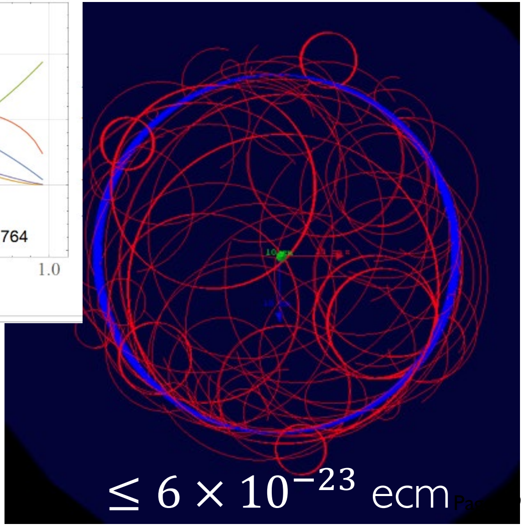
Phase II

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









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January 24, 2023

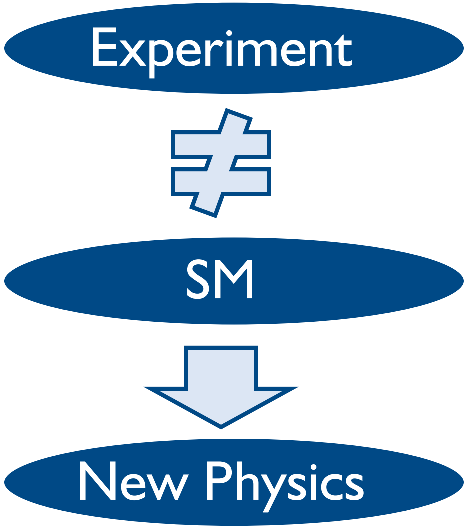
Conclusions and outlook

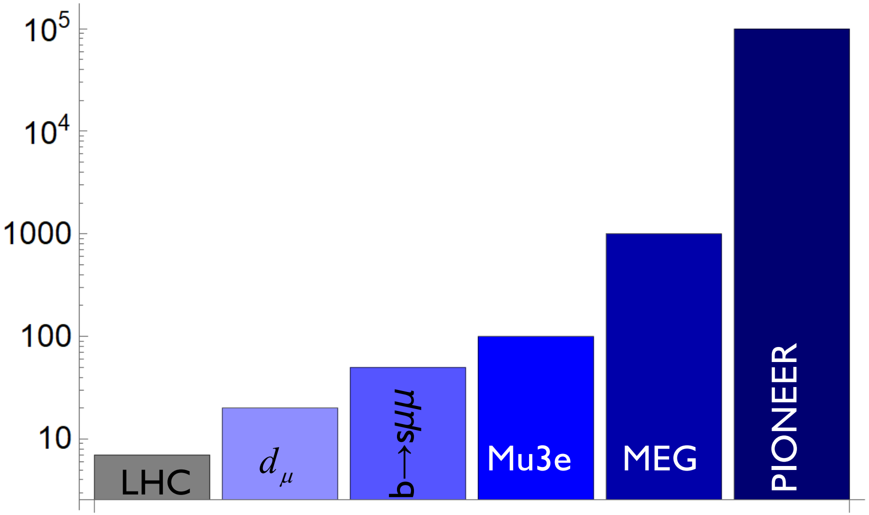
- At PSI we are setting up an experiment to demonstrate the frozen-spin technique with a sensitivity of a few **10^{-21} ecm** to the EDM of the muon
- In the next four years we will demonstrate all necessary techniques, and design a dedicated hi-fidelity solenoid
- Using muons with a moment larger than125 MeV/c and the new solenoid we will reach a sensitivity of **6**x**10^{-23} ecm**

Backup

Finding New Physics with Flavor

- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavors

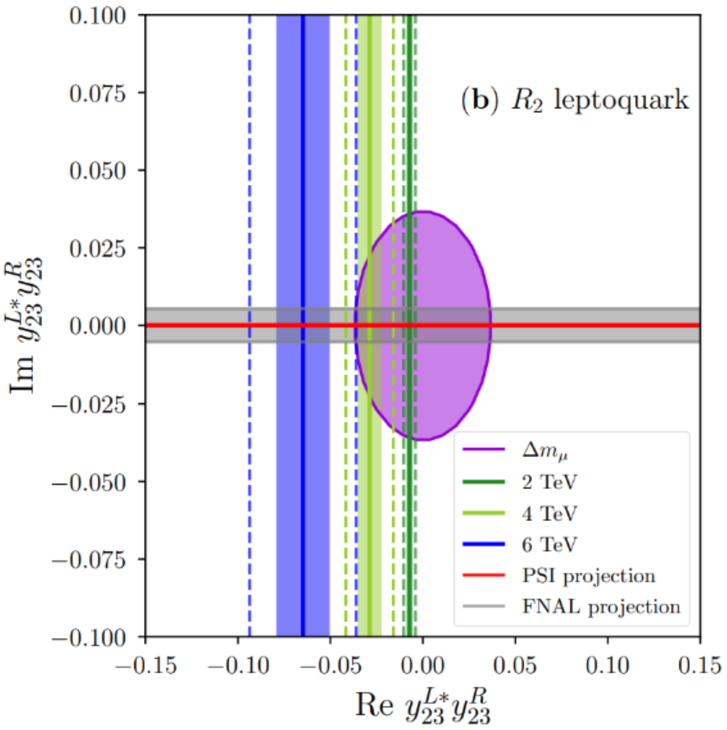




Flavor observables are sensitive to higher energy scales than collider searches

Courtesy Andreas Crivellin

Fine-Tuning?

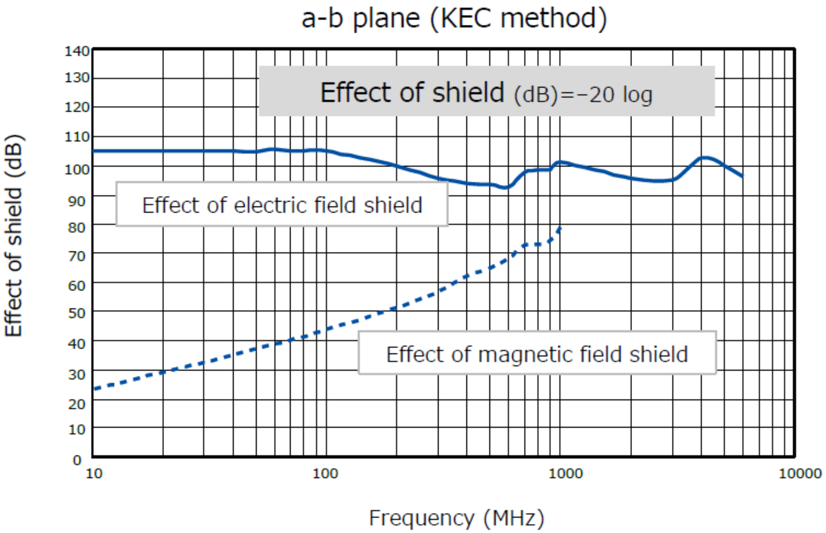


Bigaran, Volkas, 2110.03707

No signifcant tuning necessary

Courtesy Andreas Crivellin

Eddy current damping of magnetic pulse



- Exist off the shelf without substrate down to **17μm**
- Still considerable damping of magnetic pulse possible
- Tests requires
- Alternative one dimensional wires (carbon fibers / tungsten)

Multiple scattering measurement on carbon

- Characterization of potential electrode material with positrons and muons

$$50\ \mathrm{MeV}/c < p < 145\ \mathrm{MeV}/c$$