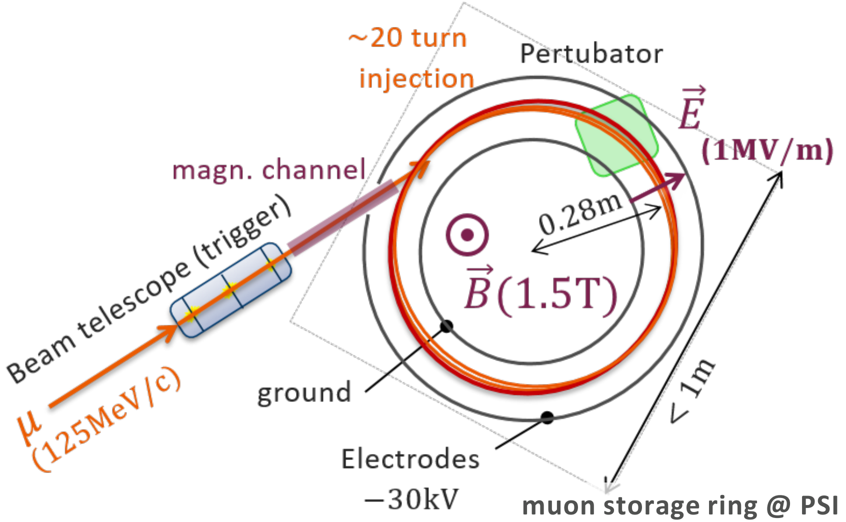
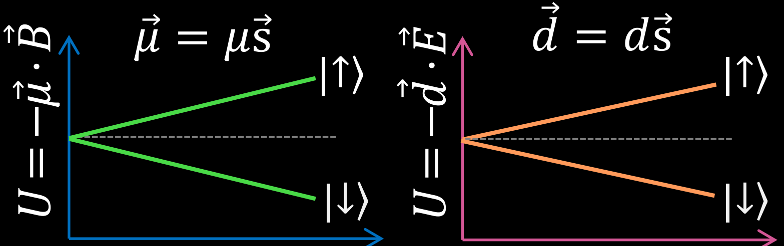


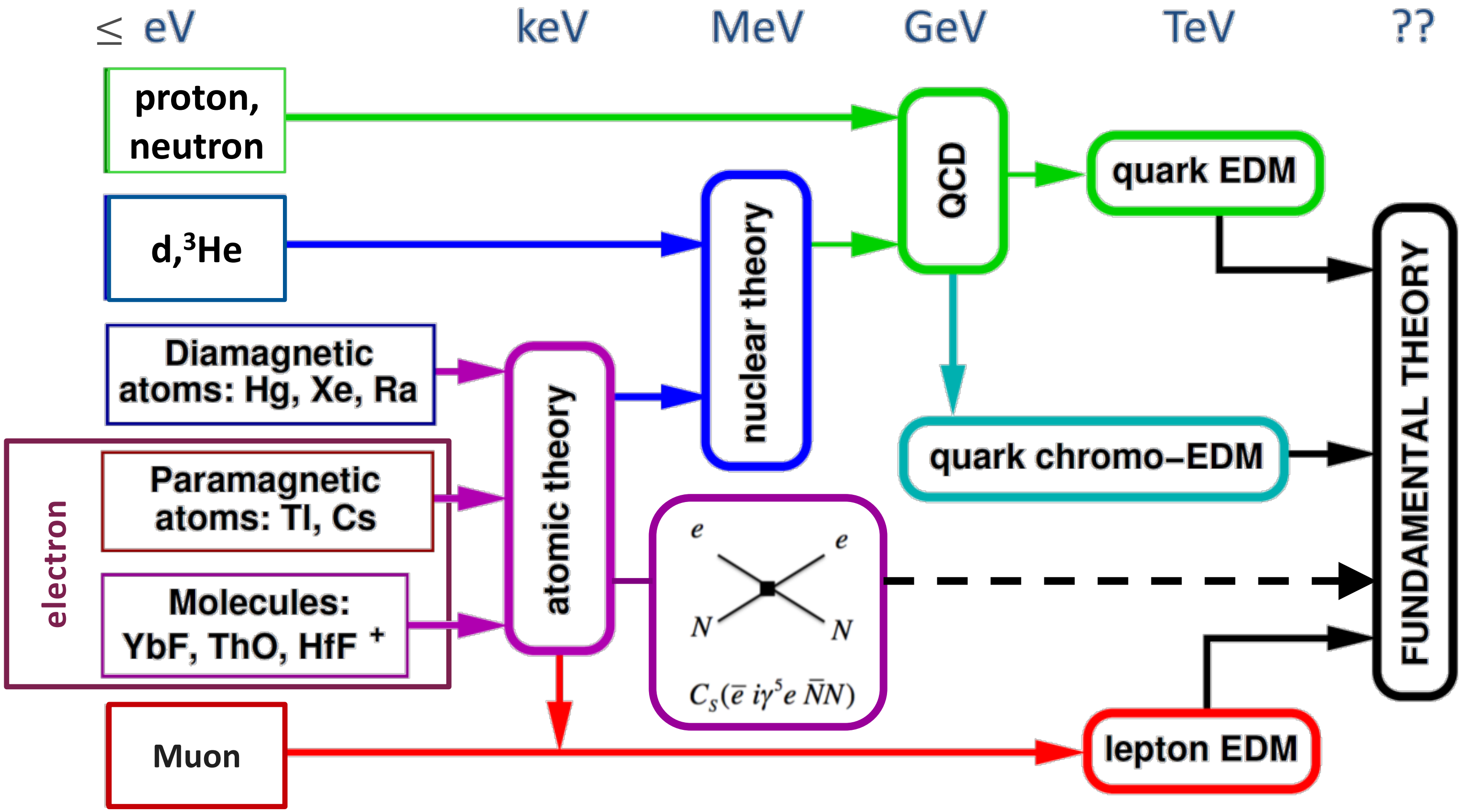
P. Schmidt-Wellenburg

Search for an electric dipole moment of the muon using a compact storage ring at PSI

CP violation & edm



Complementarity of EDM searches



Scheme: adapted from Rob G. E. Timmermans

PAUL SCHERRER INSTITUT PSI

EFT analysis of contributions to F2 and F3

magnetic-dipole Anapole - moment

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

charge electric-dipole

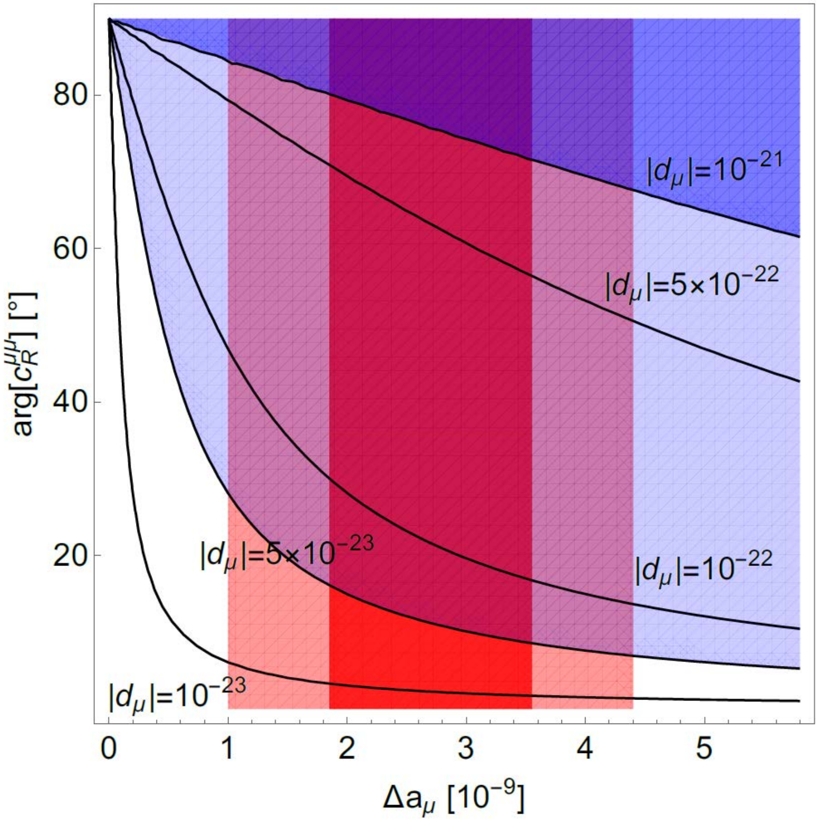
Effective Hamiltonian:

$$\mathcal{H}_{\mathrm{eff}} = c_R^{\ell_f\ell_i}\,\bar{\ell}_f\sigma_{\mu\nu}P_R\ell_i F^{\mu\nu} + \mathrm{h.c.}$$

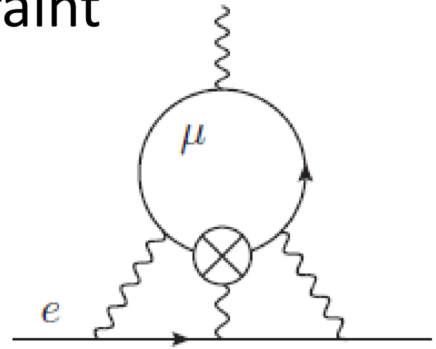
$$\delta F_2 = -\frac{2m_{\ell_i}}{e}\left(c_R^{\ell_i\ell_i} + c_R^{\ell_i\ell_i *}\right) = -\frac{4m_{\ell_i}}{e}\,\mathrm{Re}\,c_R^{\ell_i\ell_i},$$

$$F_3 = i\left(c_R^{\ell_i\ell_i} - c_R^{\ell_i\ell_i *}\right) = -2\,\mathrm{Im}\,c_R^{\ell_i\ell_i},$$

General limits on μEDM in flavor violating models



- EFT phase of Wilson parameter $c_R^{\mu\mu}$ hardly constraint



- μEDM contribution in electron EDM allows for large value: $d_\mu \leq 7.5 \times 10^{-19}\ e\text{cm}$

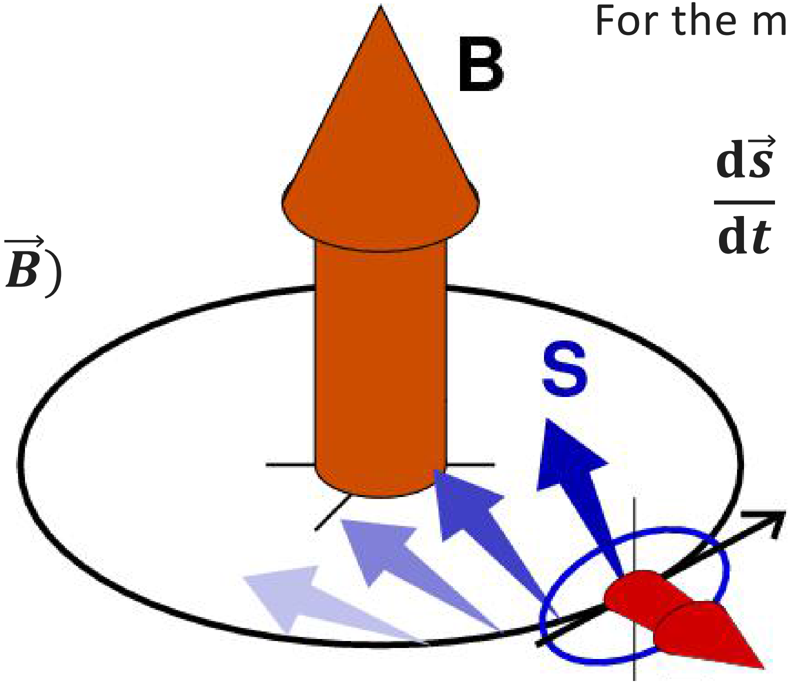
A.Crivellin, M. Hoferichter, PSW PRD 98(2018) 113002

A relativistic charged particle in a strong B-field

For the moment assume $\mu = 0$

$$\frac{\mathbf{d}\vec{\boldsymbol{p}}}{\mathbf{d}\boldsymbol{t}} = \mathbf{q}(\vec{\mathbf{v}} \times \vec{\boldsymbol{B}})$$

$$\frac{\mathbf{d}\vec{\boldsymbol{s}}}{\mathbf{d}\boldsymbol{t}} = \boldsymbol{d}\,\vec{\boldsymbol{s}}(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$$



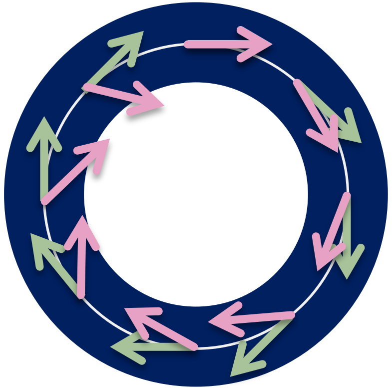
$$\vec{v} = \vec{\beta} c$$

$$\boldsymbol{E} = \boldsymbol{\gamma}\vec{\boldsymbol{\beta}}\boldsymbol{c} \times \vec{\boldsymbol{B}} \approx 0.5\ \mathrm{GV/m}$$

μ-spin precession in a $\vec{B}$ and $\vec{E}$-field

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

$\vec{\omega}_a$: spin precession in orbital plane, perpendicular to $\vec{B}$: “g-2” signal.



$\vec{\omega}_\eta$: rotation out of precession plane: “EDM signal”

η_d: is defined in analogy to magnetic moment:

$$d = \frac{\eta q \hbar}{4mc}$$

Frozen spin technique for the muon EDM

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

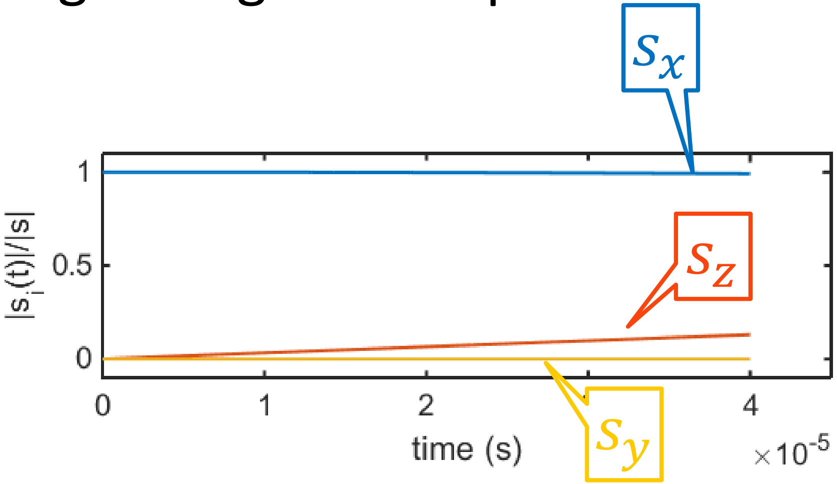
- Cancel anomalous precession with matched E-field:

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

- Spin remains parallel on orbit
- No "contamination" from anomalous spin precession

$$s_z \propto \eta E^* \cdot t$$

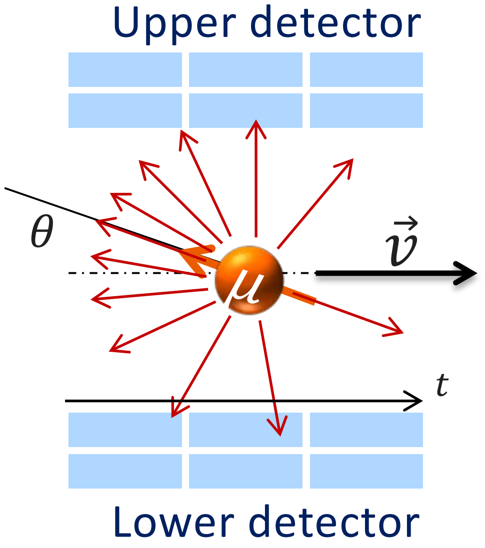
- An EDM signal is visible as growing vertical polarization



Farley *et al.*, PRL93(2004)
Adelmann *et al.*, JPG37(2010)

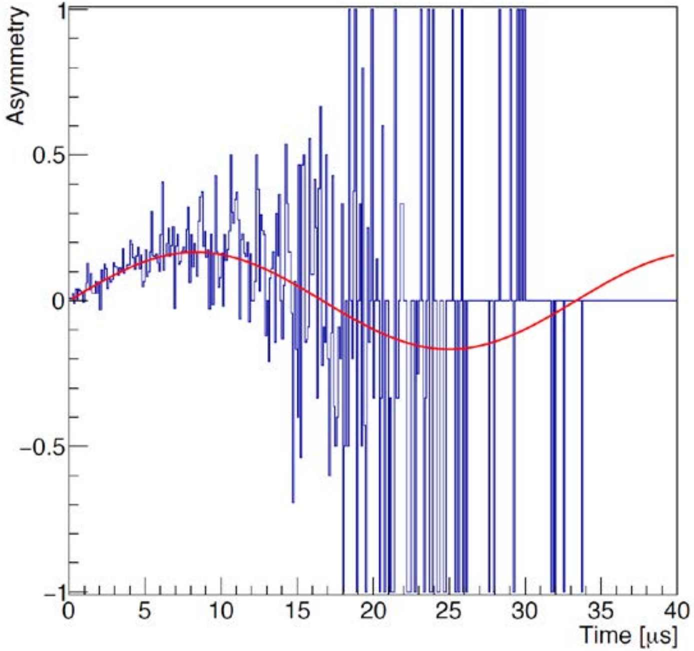
Signal: asymmetry of upper to lower detector

- Up / down detector measure decay positrons
- Side detectors (not shown) measure a_μ-precession to tune $E \cong aBc\beta\gamma^2$



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)}$$

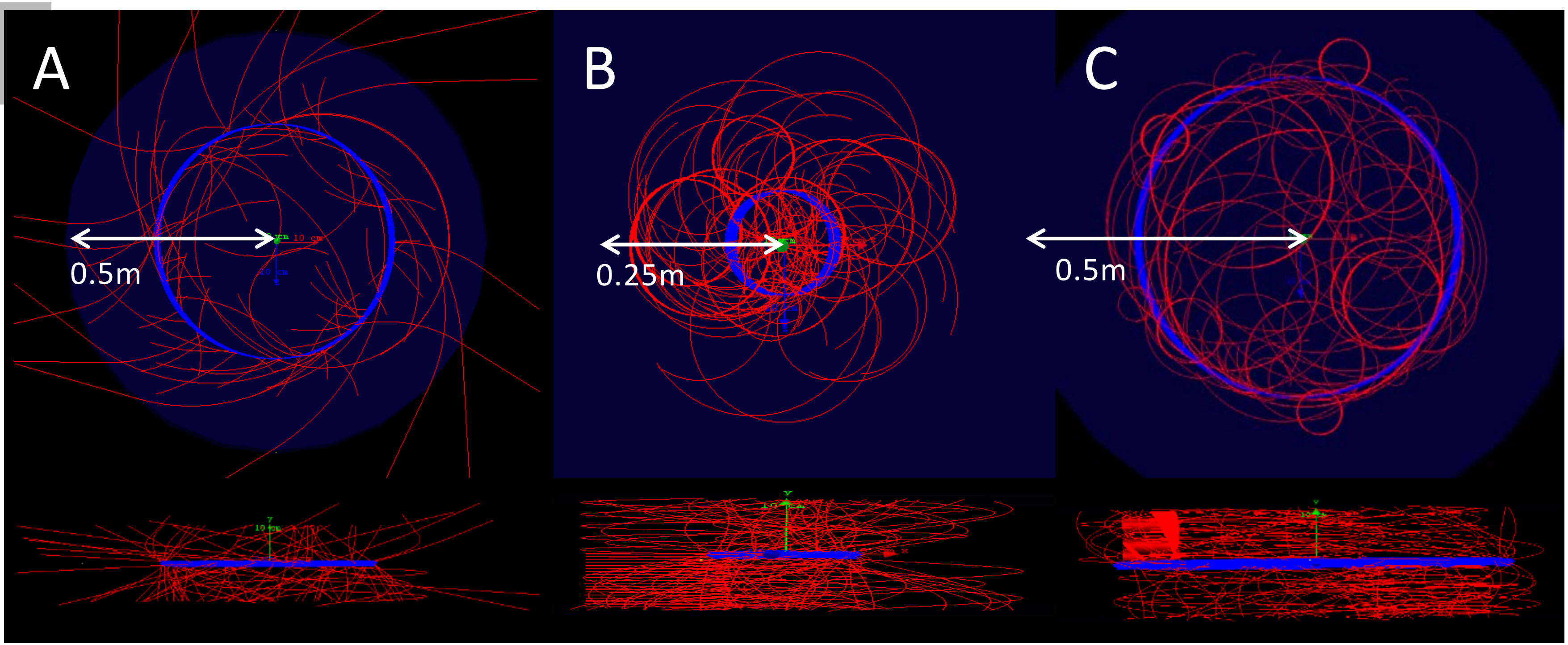


A. Adelmann *et al.* JPG 37(2010)085001

Possible scenarios

P	B	R	T

28 MeV/c, 0.34T, 0.28 m, 22ns | 28 MeV/c, 1.5T, 0.07 m, 5ns | 125 MeV/c, 1.5T, 0.28 m, 8ns

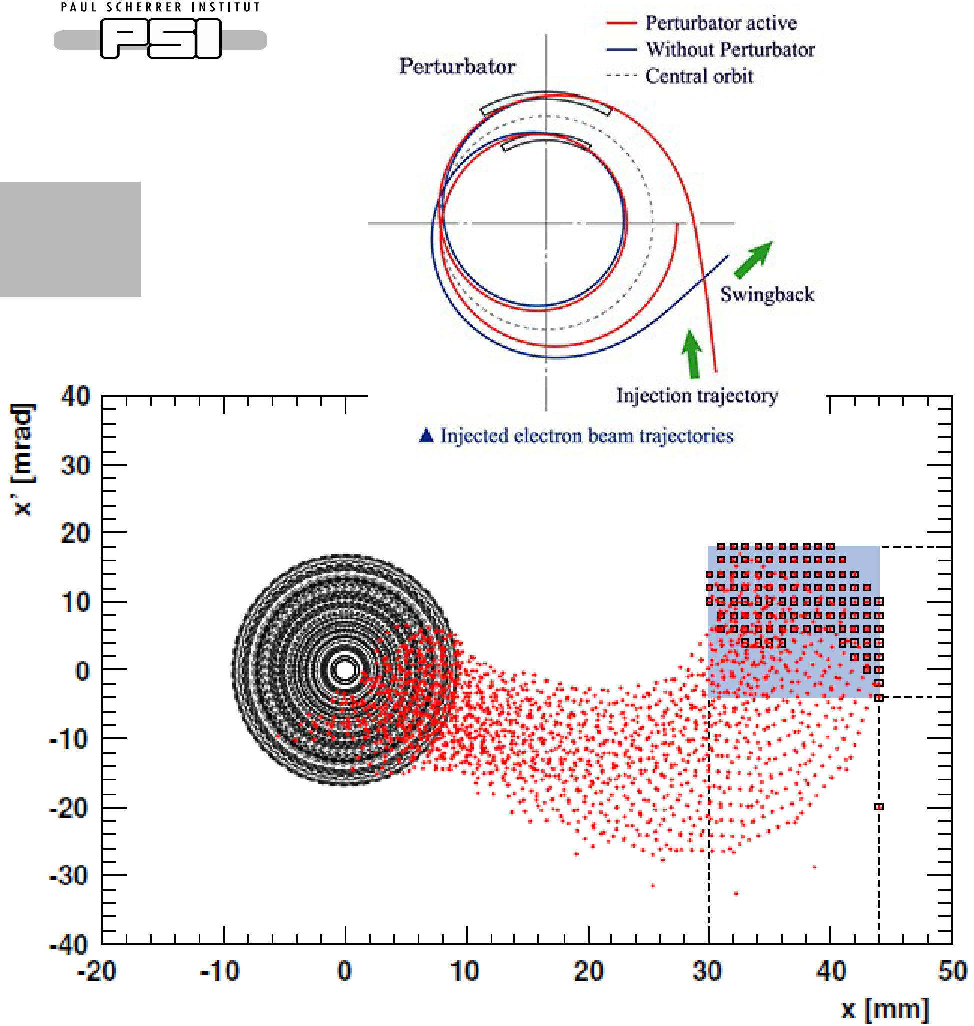


$\sigma = 78 \times 10^{-22} ecm$ | $\sigma = 2 \times 10^{-22} ecm$ | $\sigma = 5 \times 10^{-23} ecm$

Assuming $1/(\gamma\tau)$ detection rate

Simulation: Andreas Knecht

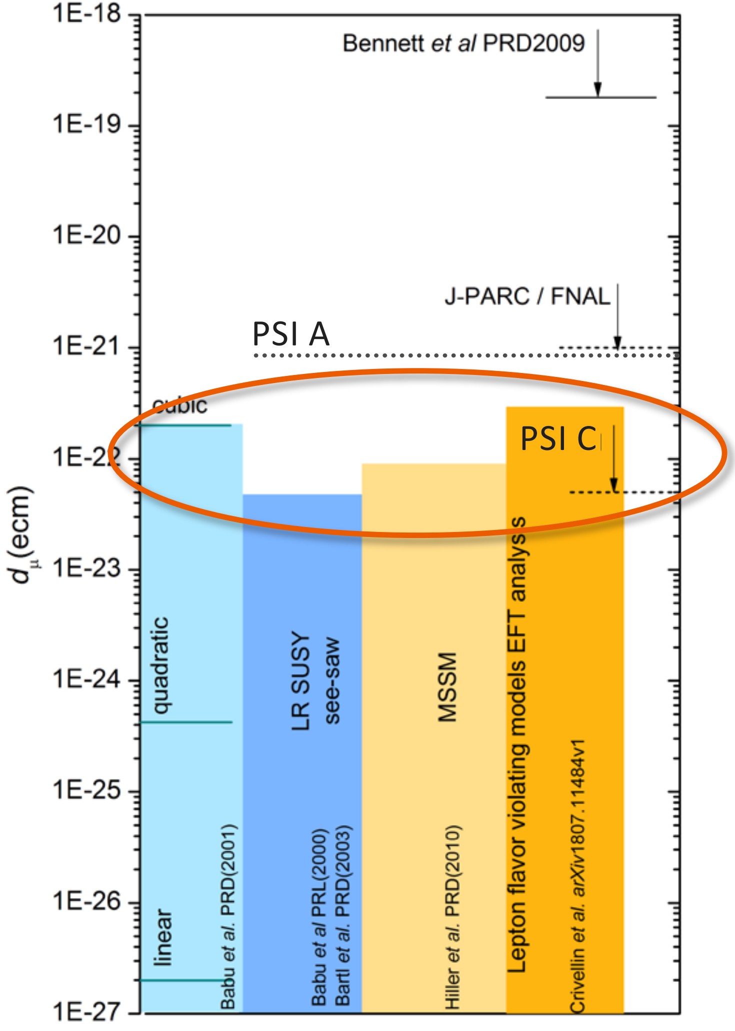
Injection



- Use weakly focusing magnet ½ integer resonance
- 20 turn resonant injection: slowly ramp down perturbator (200ns)
- Needs simulation
- Injection phase space measured for 125 MeV/c and 28MeV/c
- Need for trigger system
- Injection possible for 28MeV/c ?

- Recalculation under way

T. Takayamaet al, NIMB 24/25(1987)420



Prospects for compact μ-EDM at PSI

Apply **frozen spin technique**

- PSI μE1: $2 \times 10^8 \mu^+/s$ $\gamma = 1.57$
- Polarization from pion decay: $P = 0.9$
- Mean asymmetry of muon decay: $\alpha = 0.3$
- Compact conventional magnet:

$$B = 1.5\,T \Rightarrow R = 0.28\text{m},\, E = 10\text{MV/m}$$

$$\sigma(d_\mu) = \frac{\hbar a}{2E\tau_\mu \alpha P\sqrt{N}} = 1 \times 10^{-16}\,\frac{\text{ecm}}{\sqrt{N}}$$

- D... 00 kHz
- Ru... × 10^7 s

⇒ ... positrons per year.

PSI C sensitivity (1 year):

$$\sigma(d_\mu) < 5 \times 10^{-23}\,\text{ecm}$$

Many interesting talks and discussion in break-out groups

List of invited speakers

Nick Berger, University of Mainz

Martin Fertl, University of Mainz

Massimmo Giovannozzi, CERN

Gavin Hesketh, University College London

Kim-Siang Khaw, Tsung-Dao Lee Institute and Shanghai Jiao Tong University

Alexander Nass, Forschungszentrum Jülich

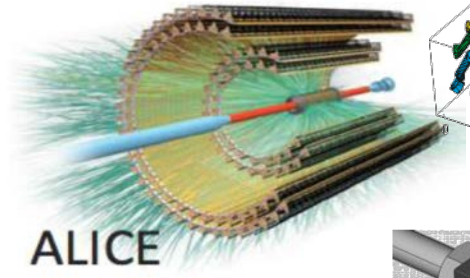
Nicola Neri, University of Milano

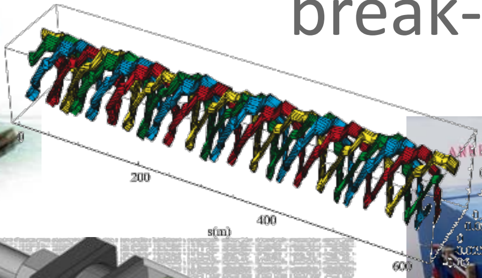
François Meot, Brookhaven National Laboratory

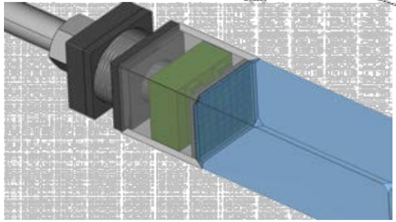
Angela Papa, University of Pisa

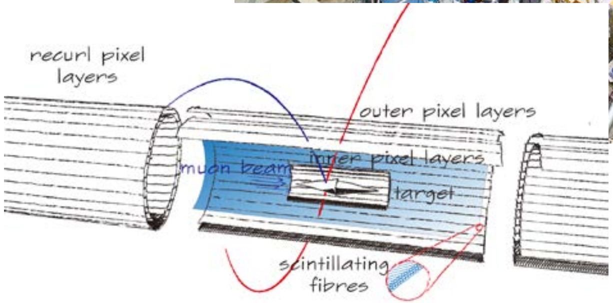
Frank Rathmann, Forschungszentrum Jülich

Peter Winter, Argonne National Lab





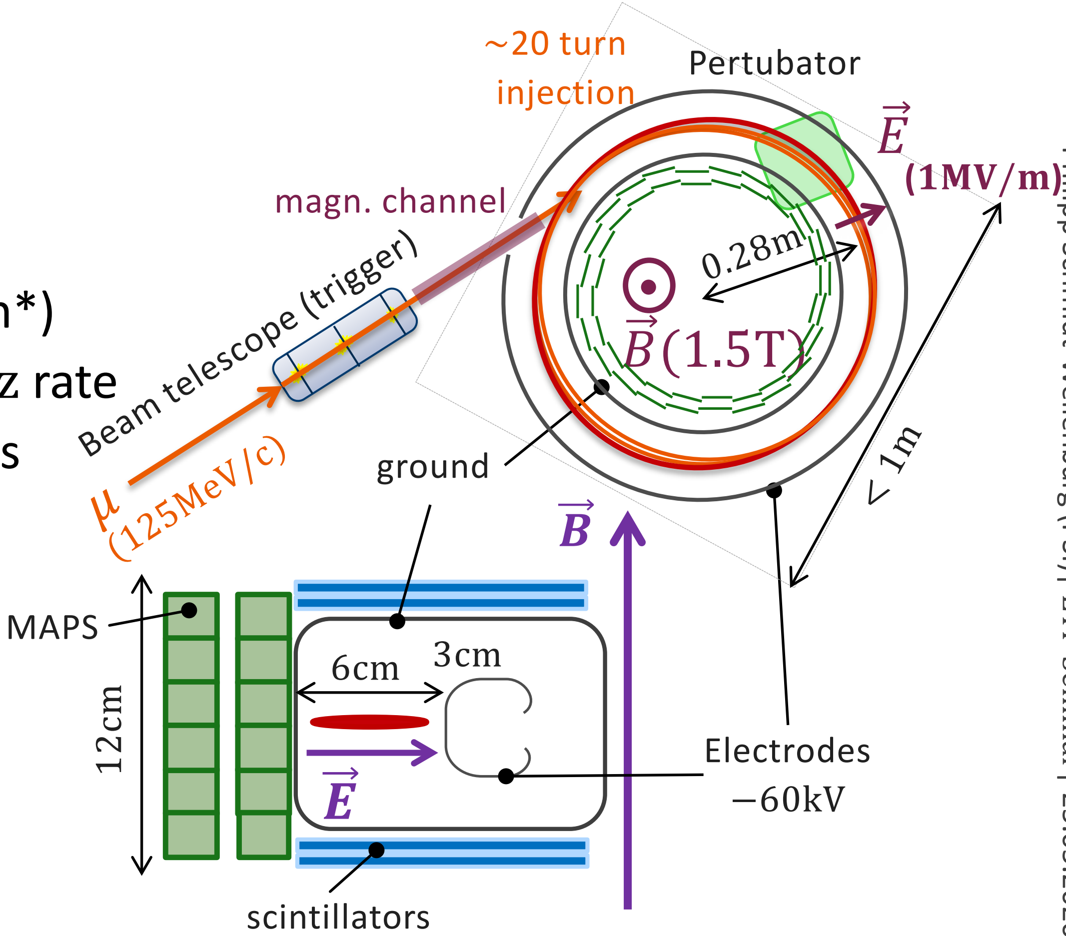




Proposal for a dedicated compact μ-EDM at PSI

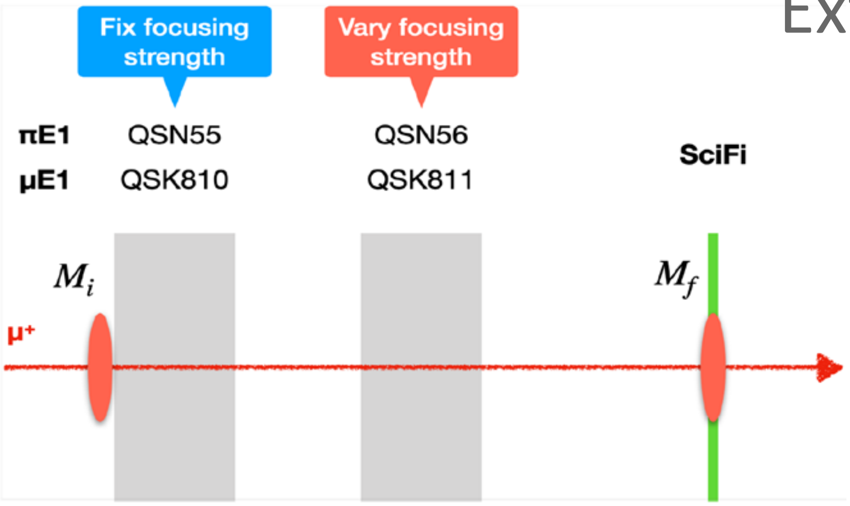
- Weak focusing magnet
- Polarized μ −beam
- Trigger from beam telescope for start of inflector ramp (resonance ½ integer injection*)
- **One** muon at a time ~200kHz rate
- Tracking detector for positrons
- Optional calorimeter

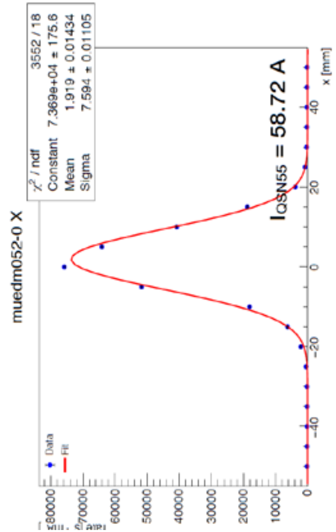
Possible detector:
Combination of scintillating tiles/fibers (timing) and thin MAPS (track, momentum)



A. Adelmann *et al.* JPG 37(2010)085001
* H. Yamada et al. NIMA467/368(2001)

Extraction of phase space





$$M_f = R \times M_i \times R^T \Leftrightarrow \begin{pmatrix} \sigma^f_{1,1} & \sigma^f_{1,2} \\ \sigma^f_{2,1} & \sigma^f_{2,2} \end{pmatrix} = \begin{pmatrix} R_{1,1} & R_{1,2} \\ R_{2,1} & R_{2,2} \end{pmatrix} \begin{pmatrix} \sigma^i_{1,1} & \sigma^i_{1,2} \\ \sigma^i_{2,1} & \sigma^i_{2,2} \end{pmatrix} \begin{pmatrix} R_{1,1} & R_{2,1} \\ R_{1,2} & R_{2,2} \end{pmatrix}$$

$$R_{QF} = \begin{pmatrix} \cos(\sqrt{|k|}l_q) & \frac{1}{\sqrt{|k|}}\sin(\sqrt{|k|}l_q) \\ -\sqrt{|k|}\sin(\sqrt{|k|}l_q) & \cos(\sqrt{|k|}l_q) \end{pmatrix}$$

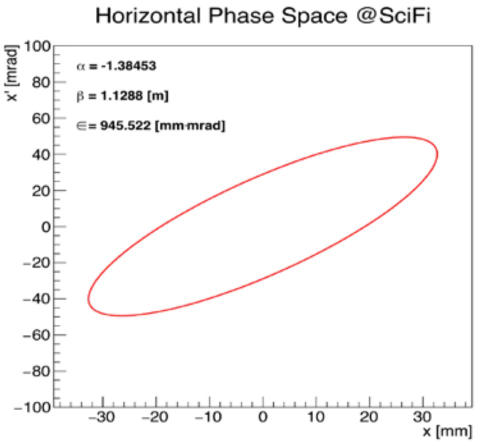
$$R_{QD} = \begin{pmatrix} \cosh(\sqrt{|k|}l_q) & \frac{1}{\sqrt{|k|}}\sinh(\sqrt{|k|}l_q) \\ \sqrt{|k|}\sinh(\sqrt{|k|}l_q) & \cosh(\sqrt{|k|}l_q) \end{pmatrix}$$

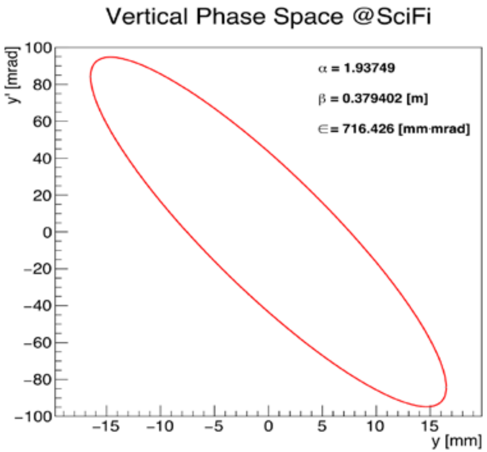
$$k \propto B(I)$$

Three quantities to determine the phase space:

$\sigma^i_{1,1}, \sigma^i_{2,2}, \sigma^i_{2,1} = \sigma^i_{1,2}$

muE1 @ 125MeV/c highest beam intensity





Highest rate measured: $5 \times 10^7 \text{Hz}$

Horizontal emittance: $2225 \text{mm} \cdot \text{mrad}$ (FWHM)

Vertical emittance : $1686 \text{mm} \cdot \text{mrad}$

Compare to "p_t of e^+" – labbooks

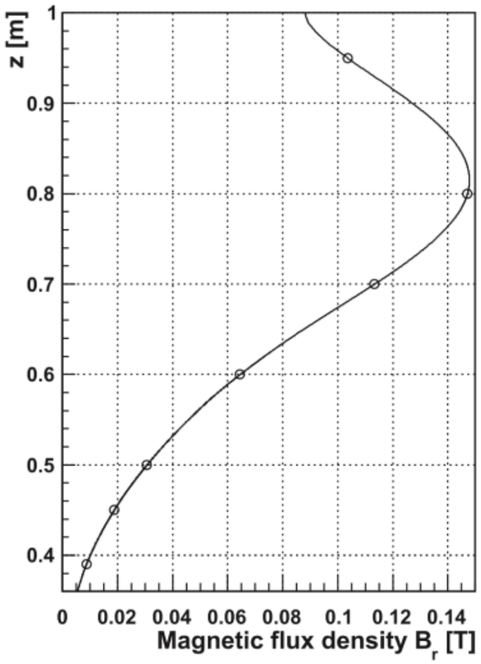
- Highest rate: $3 \times 10^8 \text{Hz}$
- Horizontal emittance: 176 to 2961 $\text{mm} \cdot \text{mrad}$
- Vertical emittance : 912 to 4275 $\text{mm} \cdot \text{mrad}$

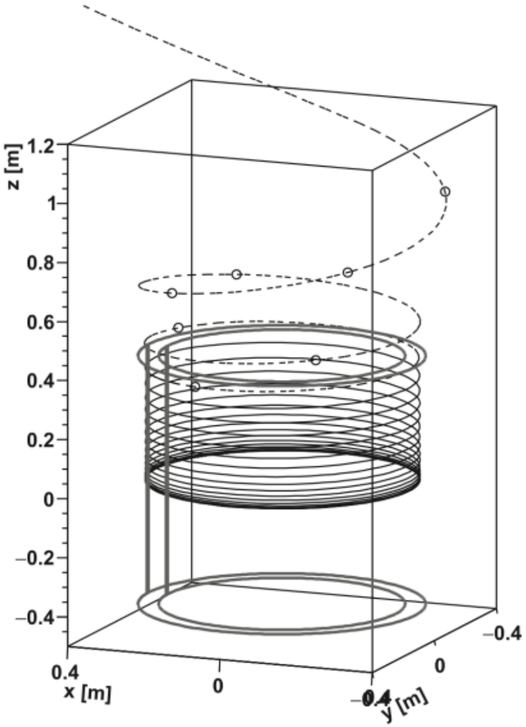
(Measured by displacement of beam profile monitor)

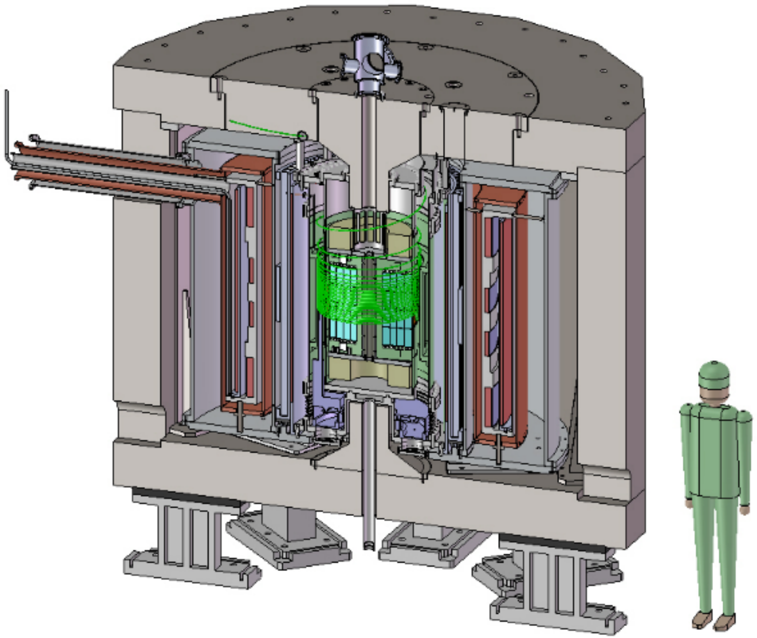
A. Adelmann et al: $28 \cdot 17 \text{ mm} \cdot \text{mrad} = 476 \text{ mm} \cdot \text{mrad}$

Inspiration by JPARC g-2 talk:

Spiral injection

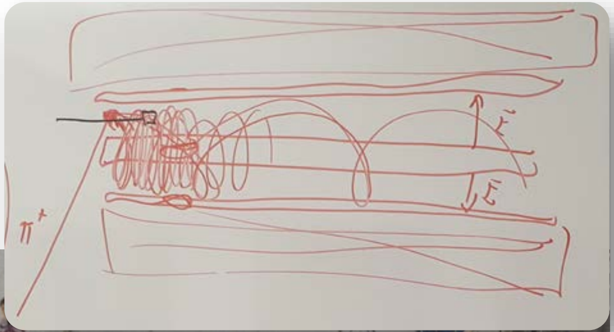




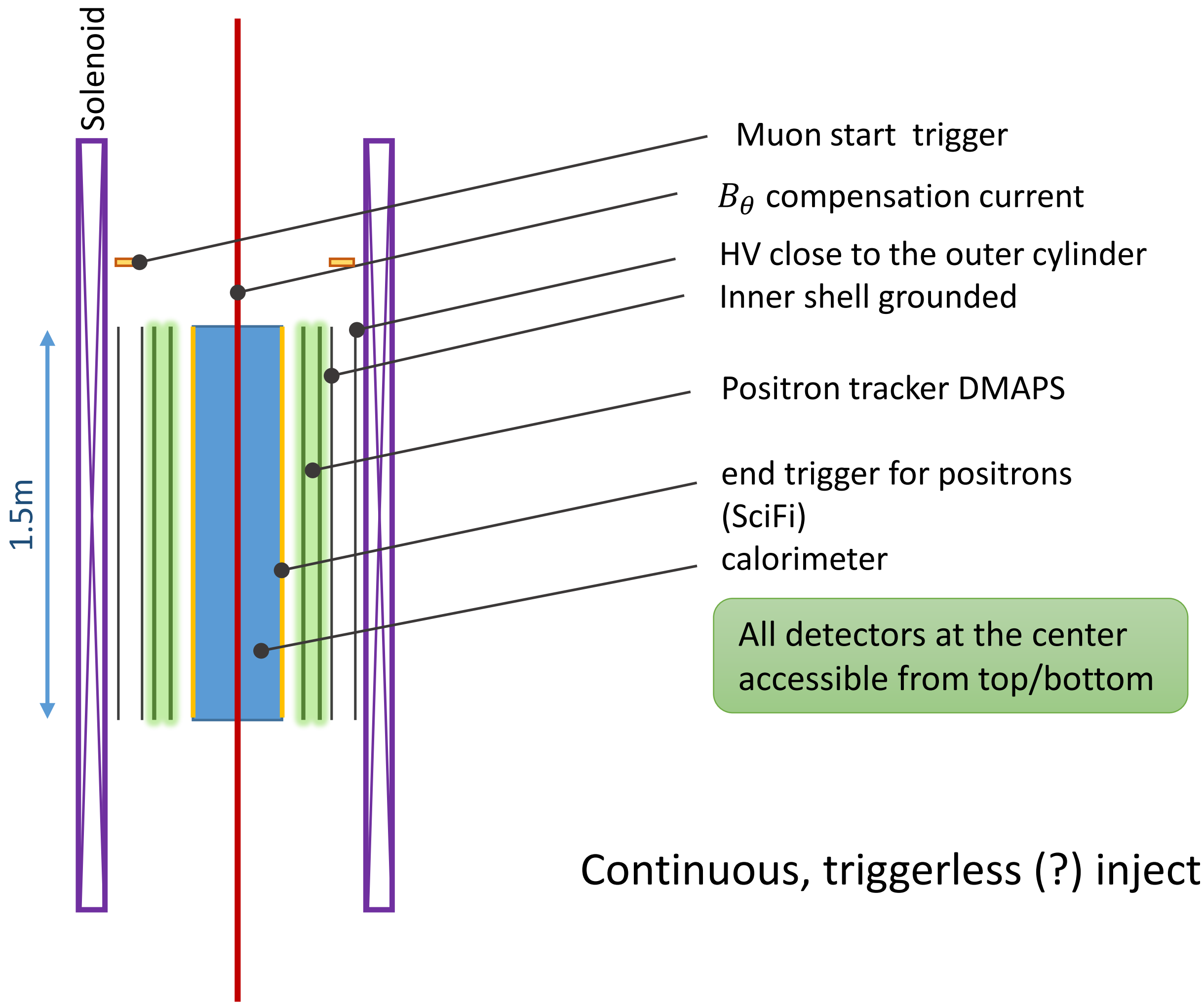


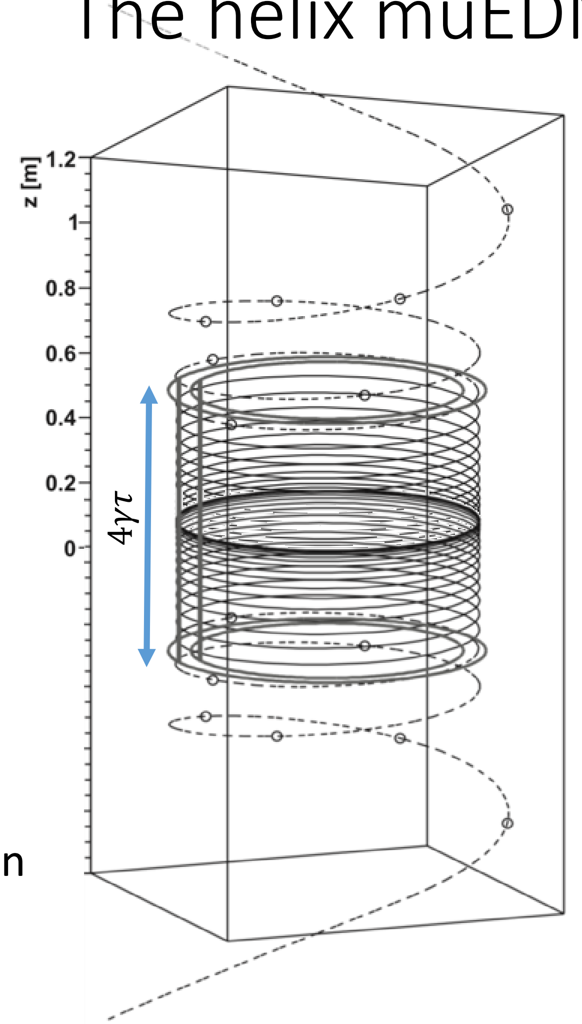
New idea during the muEDM workshop

- Use MRI magnet with high field uniformity (1 ppb/mm locally)
- Vertical injection
- Pions stop in solenoid



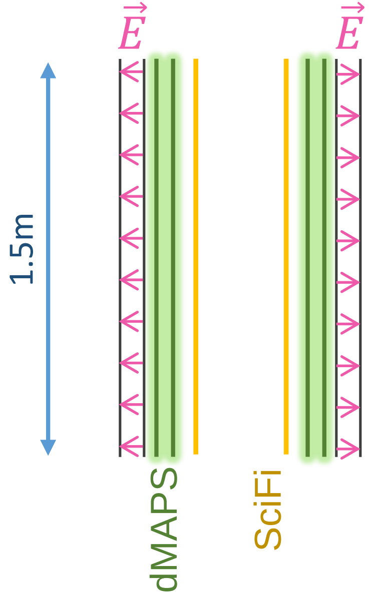
The helix muEDM





Continuous, triggerless (?) injection

Longitudinal drift velocity and tracker resolution

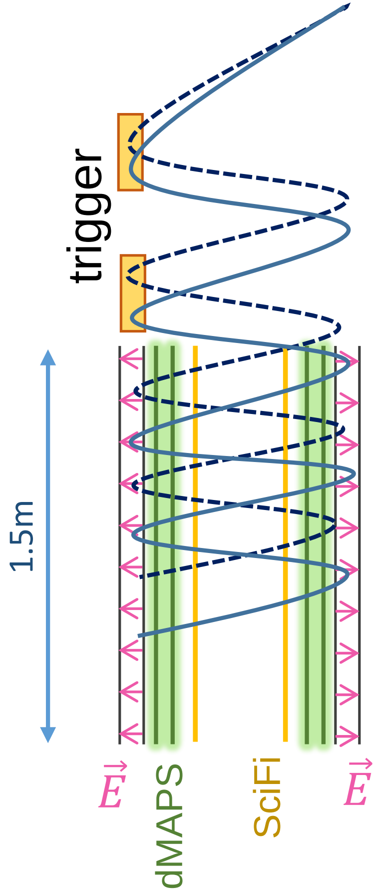


- Drift time $T = 4\gamma\tau$ for $p = 125\ \text{MeV}/c$: $T \approx 12\mu\text{s}$
- Vertical drift velocity $v_z = 125\ \mu\text{m/ns}$
- Machine frequency 50 MHz
  "Natural" time resolution of 20ns results in required spatial resolution of 2.5mm

Use vertical muon decay position as time

Continuous injection, without trigger

Divergent beam requires entrance trigger



- Several mrad divergence, e.g. → $125\,\frac{\mu m}{ns} < v_{\parallel} < 500\,\frac{\mu m}{ns}$

Continuous injection still desirable, needs trigger

- How to deal with "pile up"?
  - Current beam rates and phase space measurements make it seem unlikely that we get more than one muon every some 100 ns
  - But if you have two muons separated several 100 ns with different $v_{\parallel}$ (first slow drift, second fast drift)?

→ calculate helix trajectory? → position sensitive trigger?

→ what about multiple scattering on trigger?

→ beam time this year to measure multiple scattering.

T-BMT equation with vertical drift and frozen spin (only anomalous term)

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

$$\omega_{a,x} = \frac{e}{m}\left[aB_\theta - \left(a - \frac{1}{1+\gamma^2}\right)\zeta\frac{E}{c}\right]$$

Need to adjust with central current

$$B_\theta = \frac{E\left(1 - \frac{a}{1+\gamma^2}\right)\zeta}{c} \approx 10\ \mathrm{nT}$$

$$\omega_{a,x} = 0$$

For vertical drift $v_z/c = \zeta \ll \beta$

$$\vec{\beta} = \begin{pmatrix}\beta \\ 0 \\ \zeta\end{pmatrix} \text{ and } \vec{E} = \begin{pmatrix}0 \\ E \\ 0\end{pmatrix}$$

and

$$E = \frac{aB_z\beta c}{1-(1+a)\beta^2}$$

T-BMT equation with vertical drift and frozen spin (edm term)

$$\omega = \frac{\eta e}{2m}\left[\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right]$$

$$\omega_y = \frac{\eta e}{2m}\left[(\zeta B_\theta - \beta B) + \frac{E}{c}\right]$$

No change in “EDM-signal”, negligible smaller amplitude…..

For vertical drift $v_z/c = \zeta \ll \beta$

$$\vec{\beta} = \begin{pmatrix} \beta \\ 0 \\ \zeta \end{pmatrix}, \vec{E} = \begin{pmatrix} 0 \\ E \\ 0 \end{pmatrix} \text{ and } \vec{B} = \begin{pmatrix} B_\theta \\ 0 \\ B \end{pmatrix}$$

and

$$E = \frac{aB_z\beta c}{1-(1+a)\beta^2}$$

for $E = 10\text{kV/cm}$ and $\zeta = \frac{\beta}{1000} \quad \rightarrow \quad B_\theta = 10\text{nT}$

The muon EDM workshop

- 37 participants
- 11 invited talks on:
  - Beam dynamics
  - Storage rings
  - EDM measurements
  - Detector technology

Output:

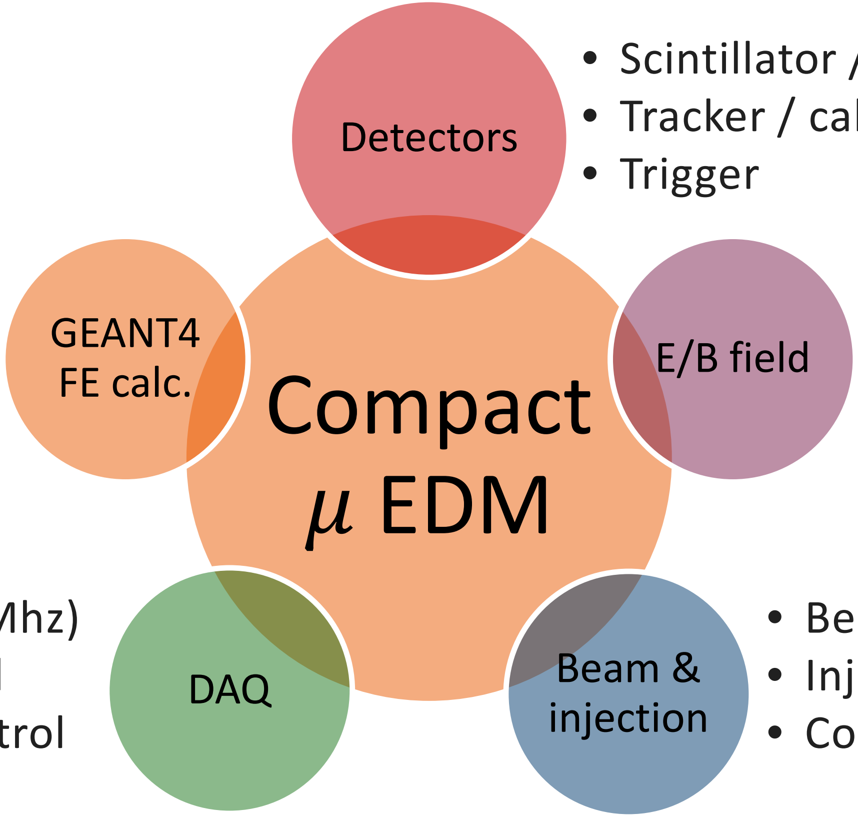
- New ideas
- List of action items
- Core muEDM project team
- Statement of interest to participate by several Groups

Letter of Intent when most important open questions are resolved

Many challenges (a incomplete collection)

- **Injection**
  - **Study resonant injection** using a non-linear magnetic field perturbation
  - **Study vertical injection** a la JPARC
- **Injection trigger**
  - Too short timing between detection of “suitable” muon and ramp of pertubator
- **Detector**
  - High B-field, minimal spacing, access difficult, high heat load
  - Minimal material budget (multiple scattering) / stop positrons in scintillator / calorimeter?
- **Magnet**
  - Very good uniformity (<1ppm) because of systematic with vertical weak focusing
  - Extreme uniformity (few ppb) for helix approach
- **3D Magnetic field characterization**
  - Measurement of field along orbit on 1uT at 1T (NMR /He3 ???)

Lets build a collaboration!



- Scintillator / Silicon
- Tracker / calorimeter
- Trigger

- Full Geant4 Model
- Design + FE model
- Systematic studies
- DAQ simulator

- Magnet & PS
- E-field electrodes
- Sensors (NMR)
- Magnet shimming

- Fast DAQ (at 100 Mhz)
- Experiment control
- Environmental control

- Beam line
- Injection scheme
- Coils & power supplies

Interested and active partners: Geneva, Jülich, Liverpool, London, Mainz, Manchester, Pisa, Roma, Shanghai, ETHZ

Thank you for your attention

Thanks to all μEDM aficionados:

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K. Kirch (PSI/ETHZ), R. Khasanov (PSI),
A. Knecht (PSI), M. Meier (PSI),
A. Papa (PSI/ U. Pisa), A. Pratyush (ETHZ),
C. Petitjean (PSI), M. Sakurai (ETHZ),
K.-S. Khaw (SJTU)