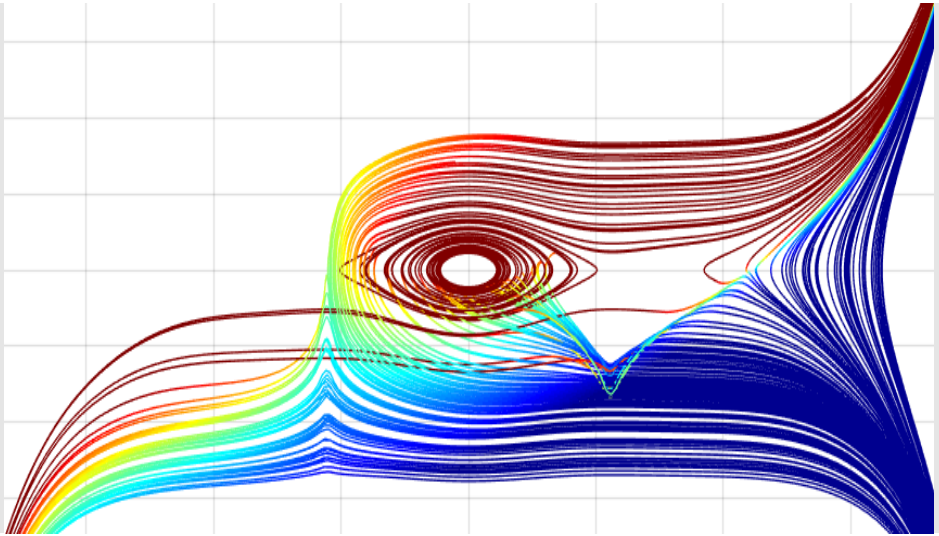
PAUL SCHERRER INSTITUT

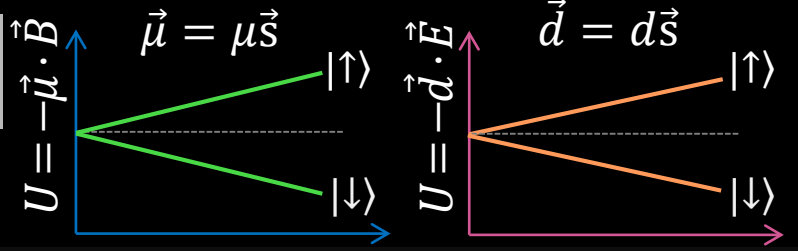
PSI



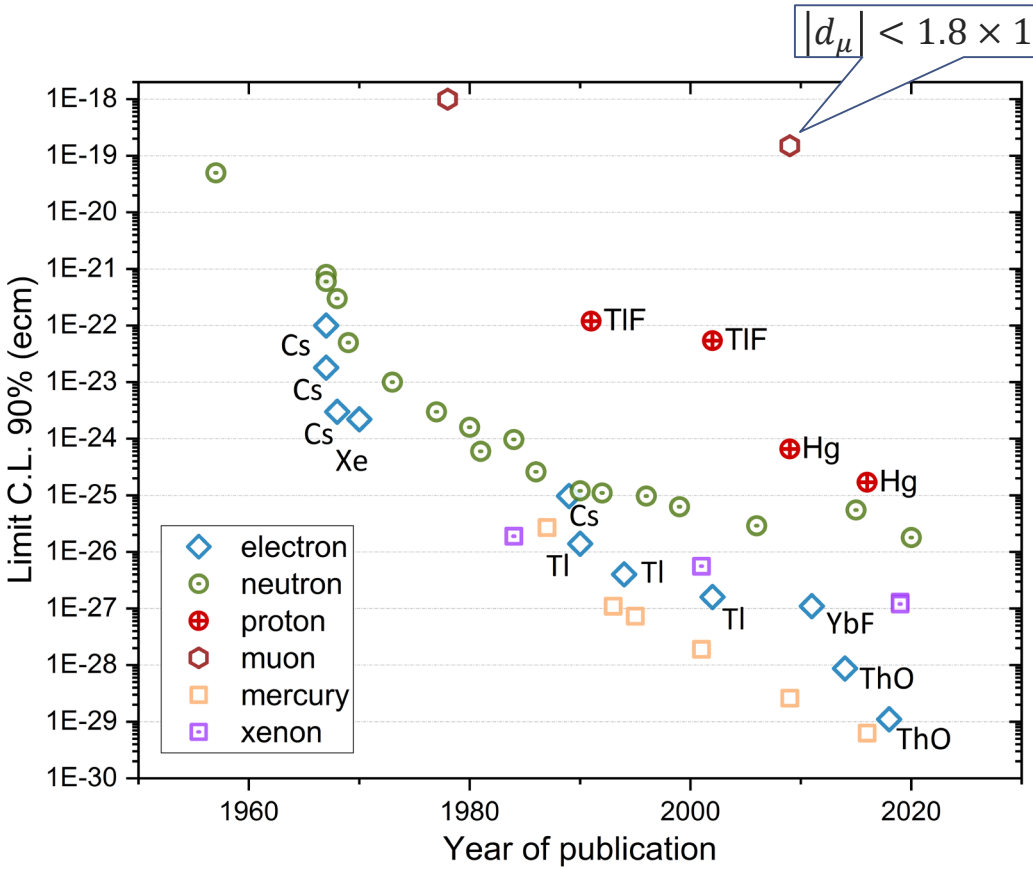
P. Schmidt-Wellenburg

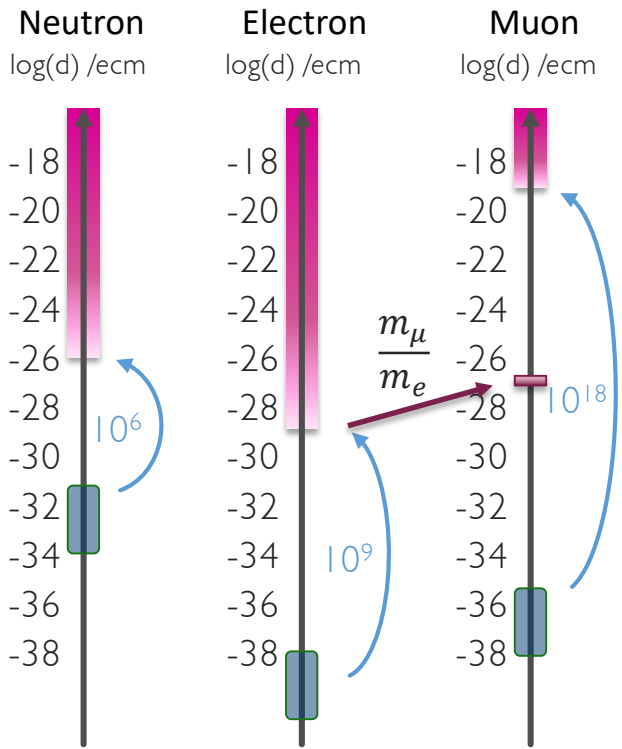
Search for the muon EDM using the frozen-spin technique

CP violation & edm



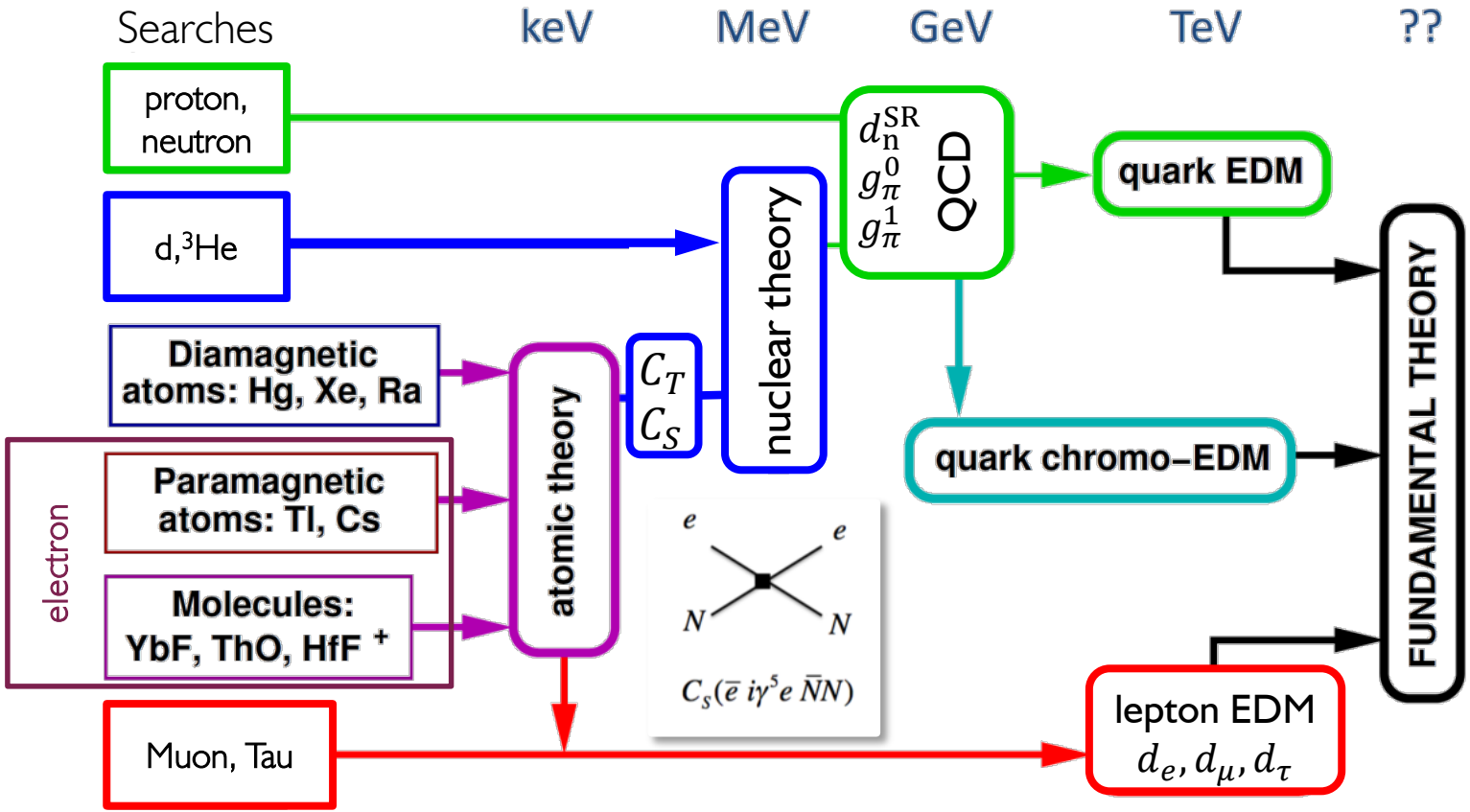
A brief history of EDM searches





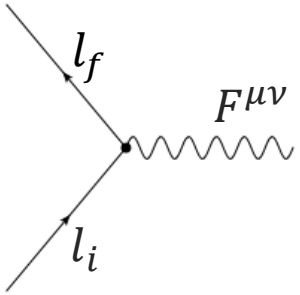
* Bennett et al., PRD80(2009)052008

Complementarity of EDM searches



Scheme: adapted from Rob G. E. Timmermans

EFT analysis of contributions to F2 and F3



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

magnetic-dipole

Anapole - moment

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

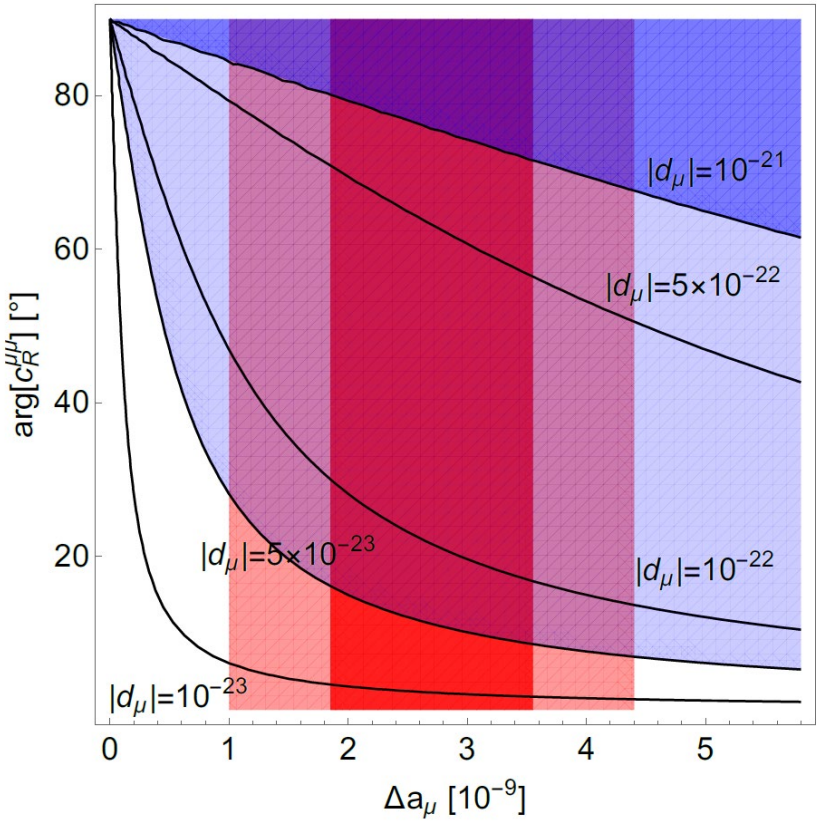
charge

electric-dipole

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

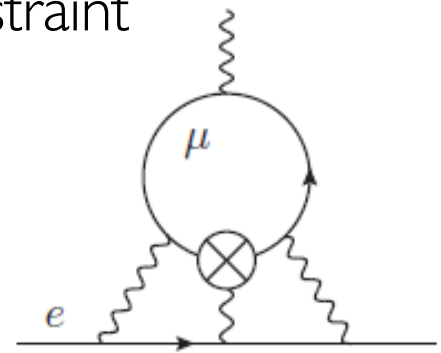
$$F_3 = d_{l_i} = i \left(c_R^{l_i l_i} - c_R^{l_i l_i *} \right) = -2 \text{Im}\, c_R^{l_i l_i}$$

Limits on μEDM in lepton flavor violating models



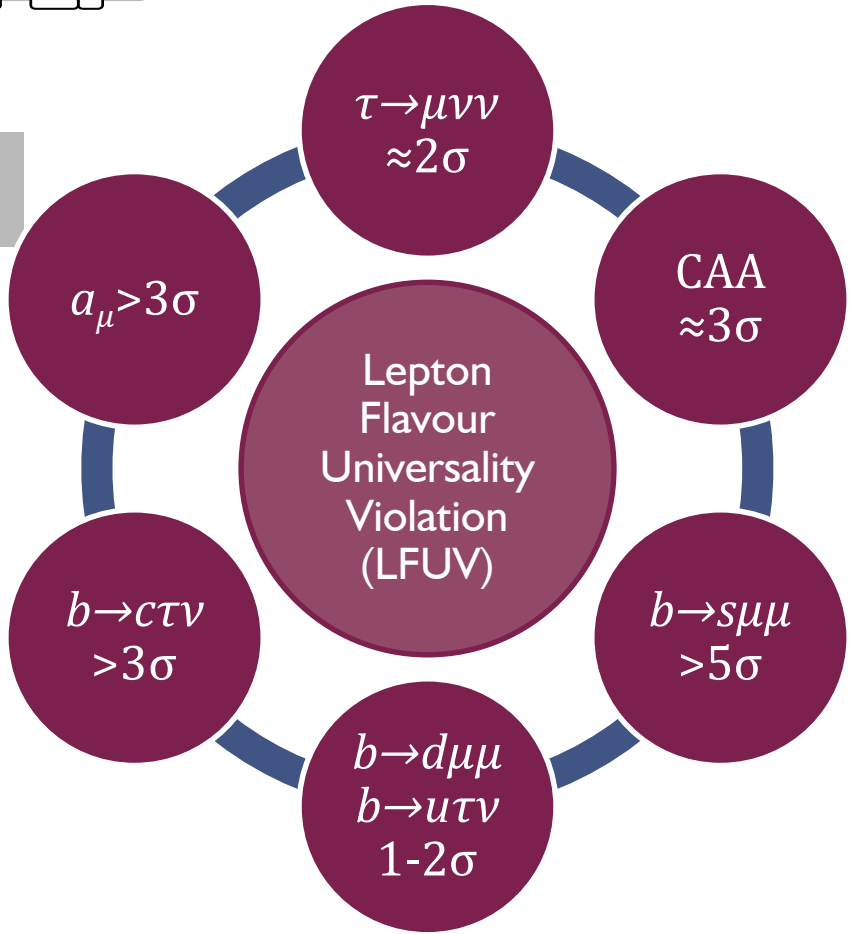
A.Crivellin, M. Hoferichter, PSW PRD 98(2018) 113002

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



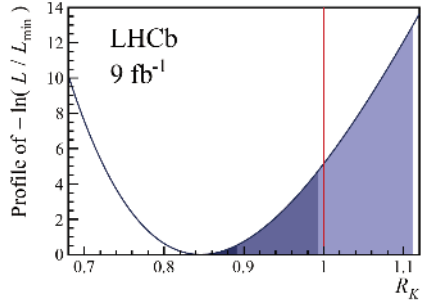
- μEDM contribution in electron EDM allows for large value: $d_\mu \leq 7.5 \times 10^{-19}\ e\text{cm}$

Hints of new physics



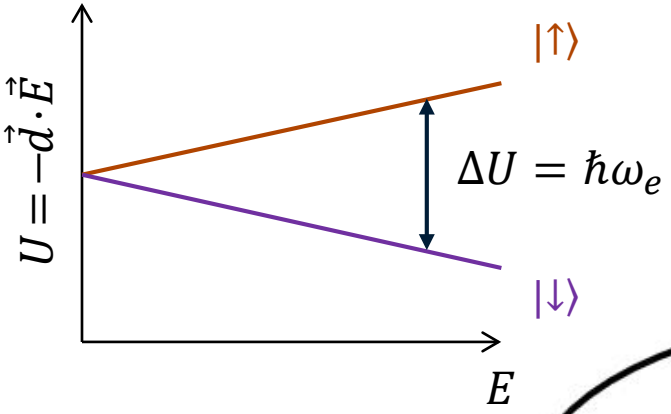
- Decay of B-mesons at LHC Babar and Belle deviate from SM expectation
- Tension in $\tau \to \mu\nu\nu$
- Cabibbo-angle anomaly might be a indication of LFUV
- Anomalous magnetic moment of muon deviates from SM

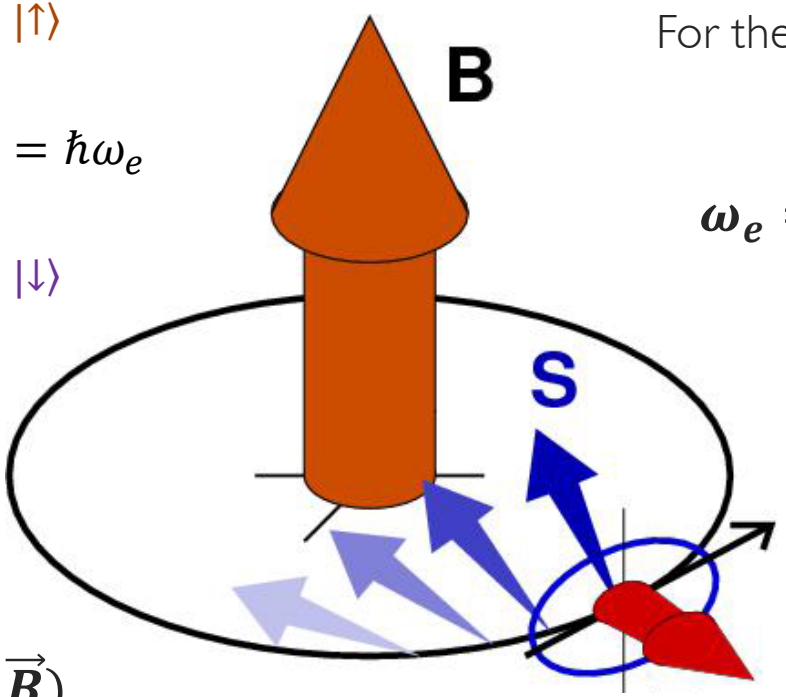
3.1σ evidence of LFUV in $B^+ \to K^+\ell^+\ell^-$



B. Capdevilla et al, JHEP01(2018093
LHCb, arXiv:2103.11769v1

A relativistic charged particle in a strong B-field





For the moment assume $\mu = 0$

$$\omega_e = \frac{d\vec{s}}{dt} = d\,\vec{s}(\vec{v} \times \vec{B})$$

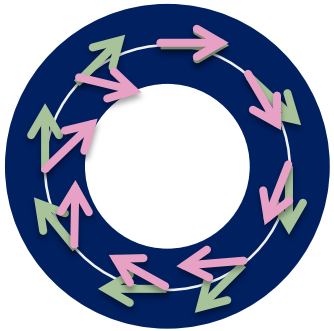
$$\vec{v} = \vec{\beta} c$$

$$\frac{d\vec{p}}{dt} = q(\vec{v} \times \vec{B})$$

$$E = \gamma\vec{\beta}c \times \vec{B} \approx O(1\mathrm{GV/m})$$

Frozen spin technique for the muon EDM

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



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

The g-2 experiment: measuring with magic momentum

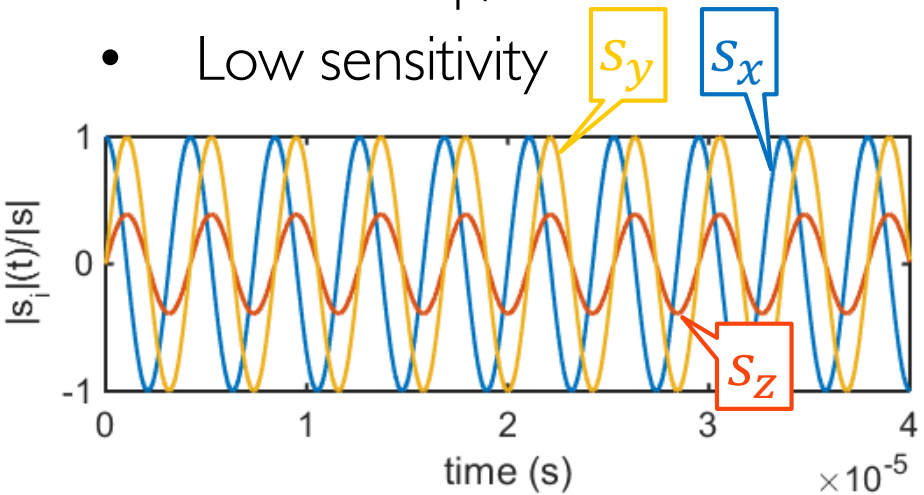
$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta_d}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

- Run at "magic-moment" $p_\mu = 3.1\mathrm{GeV}/c$ → can use E-fields for tuning ($E/c \ll \boldsymbol{\beta}\times\boldsymbol{B}$)
- Assume η small

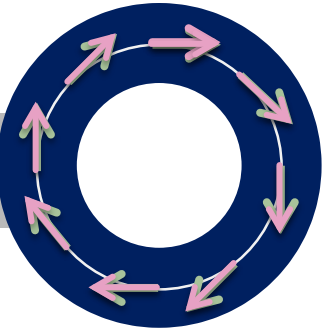
  → direct access to a_μ from

$$\omega_a = q a_\mu \vec{B}/m$$

- An EDM signal would be visible as up/down oscillation
- Low sensitivity



Frozen spin technique for the muon EDM



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

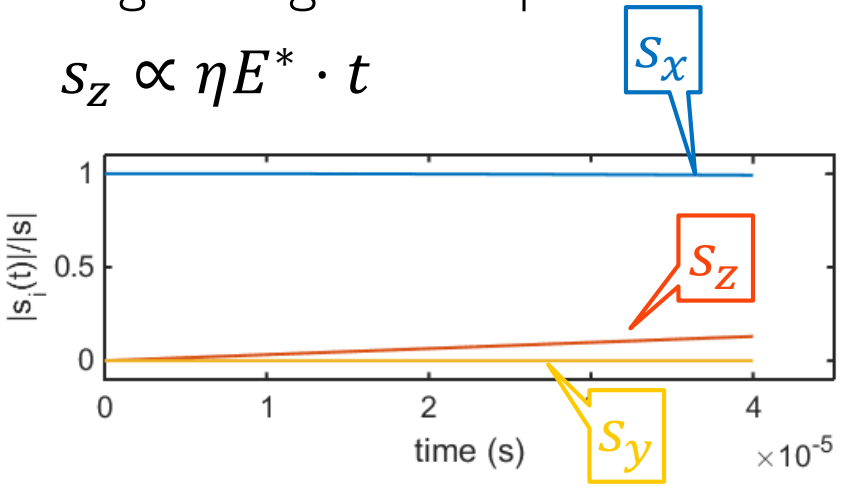
- Cancel anomalous precession with matched E-field:

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

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

- An EDM signal is visible as growing vertical polarization

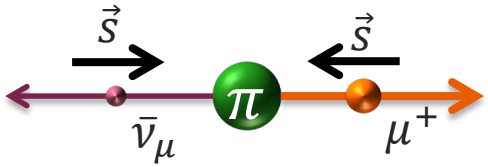
$$s_z \propto \eta E^* \cdot t$$



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

μ-polarization and analysis

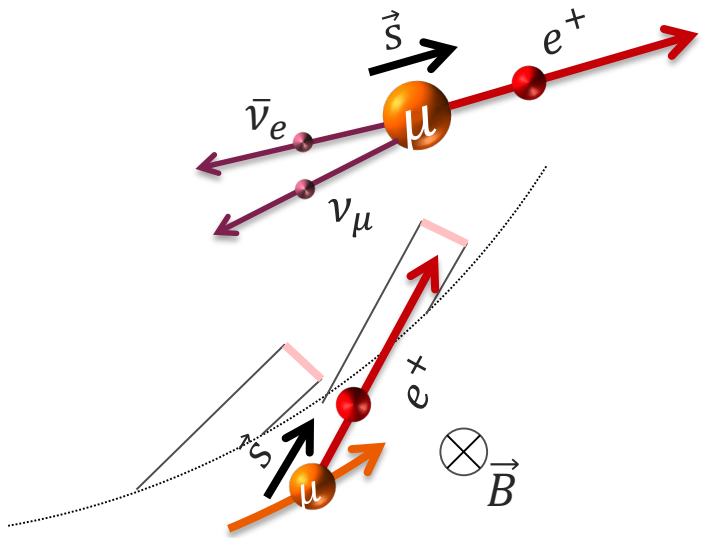
- Weak decay $\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ result in $P_\mu \approx 95\%$ for $p_\pi \sim 220\mathrm{MeV}/c^2$ backward decay in $P_\mu \approx 95\%$



- Weak decay $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ results in decay asymmetry

$$\bar{\alpha} \approx 0.3$$

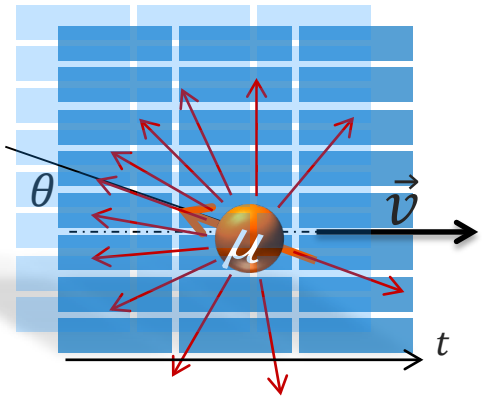
- Detection of e^+ of decay (for EDM vertical resolution)

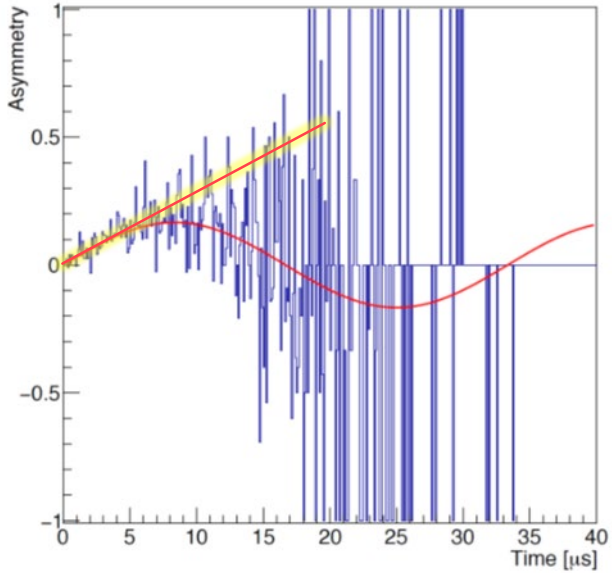


Signal: asymmetry up/downwards tracks with time

- Positron tracker measures up-down asymmetry decay positrons $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ (V-A asymmetry)
- Same detector measures a_μ-precession to tune $E_\mathrm{f} \cong aBc\beta\gamma^2$

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



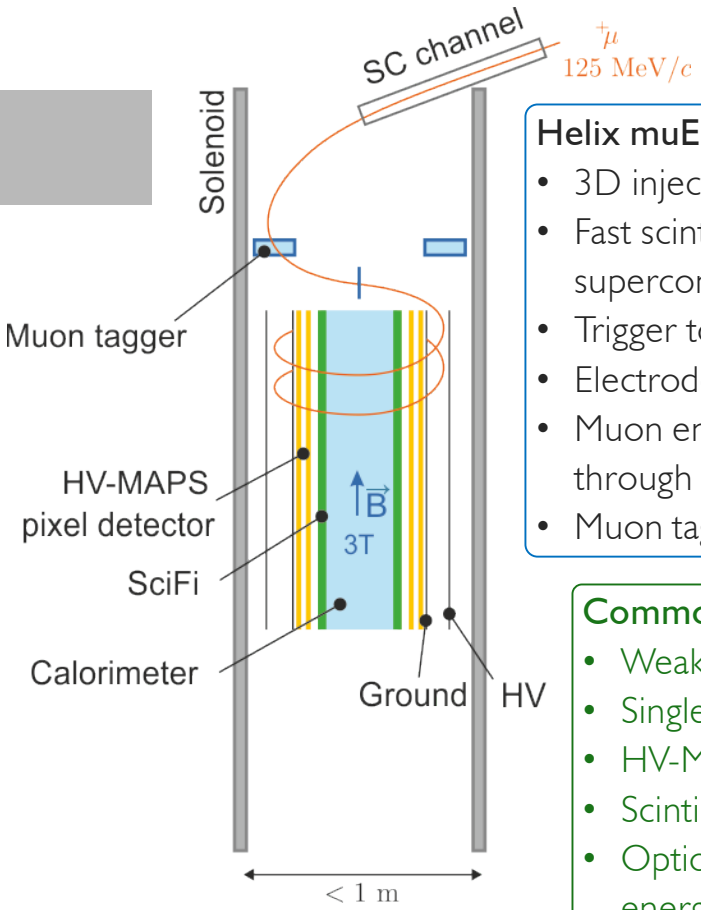


The slope gives the sensitivity of the measurement:

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

P := initial polarization
E_f := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_μ := lifetime of muon
α := mean decay asymmetry

Two concepts for a muon EDM at PSI

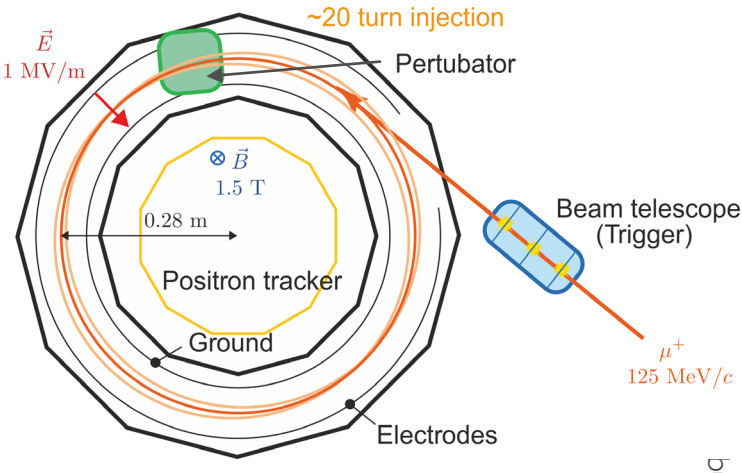


Helix muEDM

- 3D injection into uniform 3T-field
- Fast scintillator trigger in superconducting channel
- Trigger to kick time >50ns
- Electrodes far away from injection
- Muon enters from top, no passage through electrodes
- Muon tagger for track ID

Common features

- Weak focusing field
- Single muon per storage
- HV-MAPS positron tracking
- Scintillator for fast "End" signal
- Optional calorimeter for energy resolution



Lateral muEDM storage ring

- Lateral injection into uniform 1.5T-field
- Fast scintillator trigger upstream in beamline
- Trigger to kick time <10ns
- Muon enter with multiple passages through electrodes/material (losses/scattering)
- Injection channel close to HV electrode
- Low field in injection zone perturbs injection

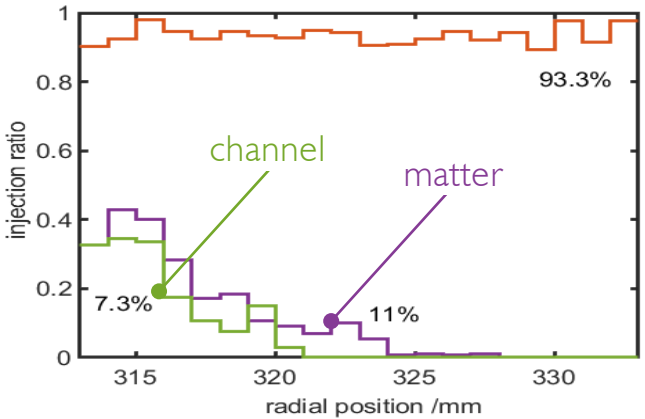
H. Iinuma *et al.*, NIMA832(2016)

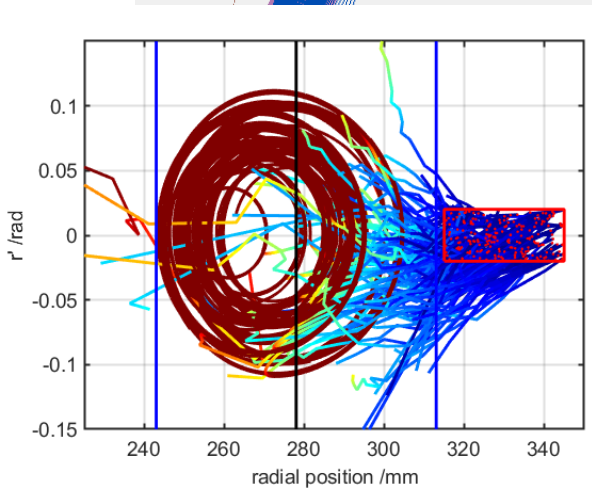
A. Adelmann *et al.*, JPG37(2010)

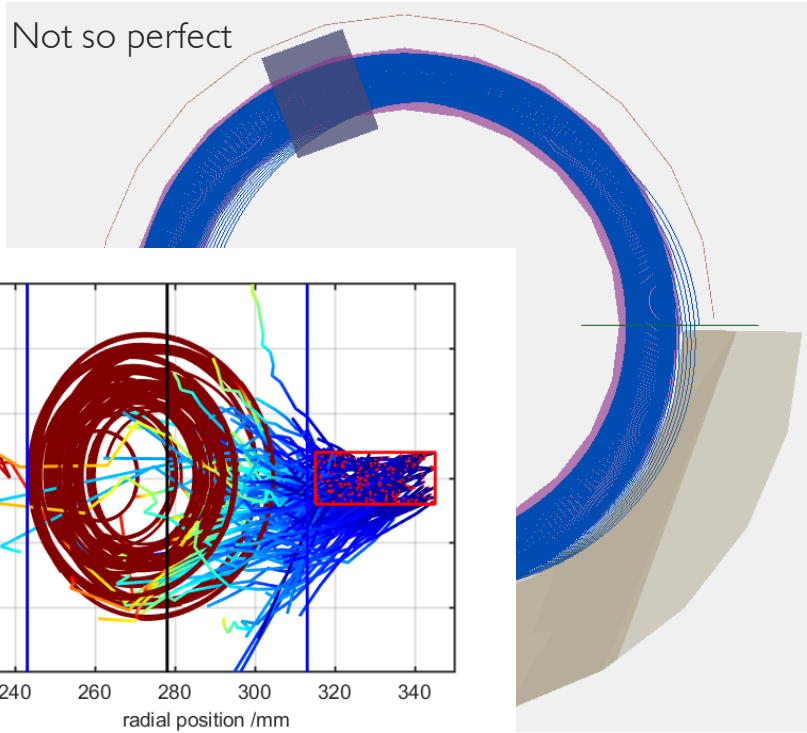
Simulation and injection efficiency

Lateral injection

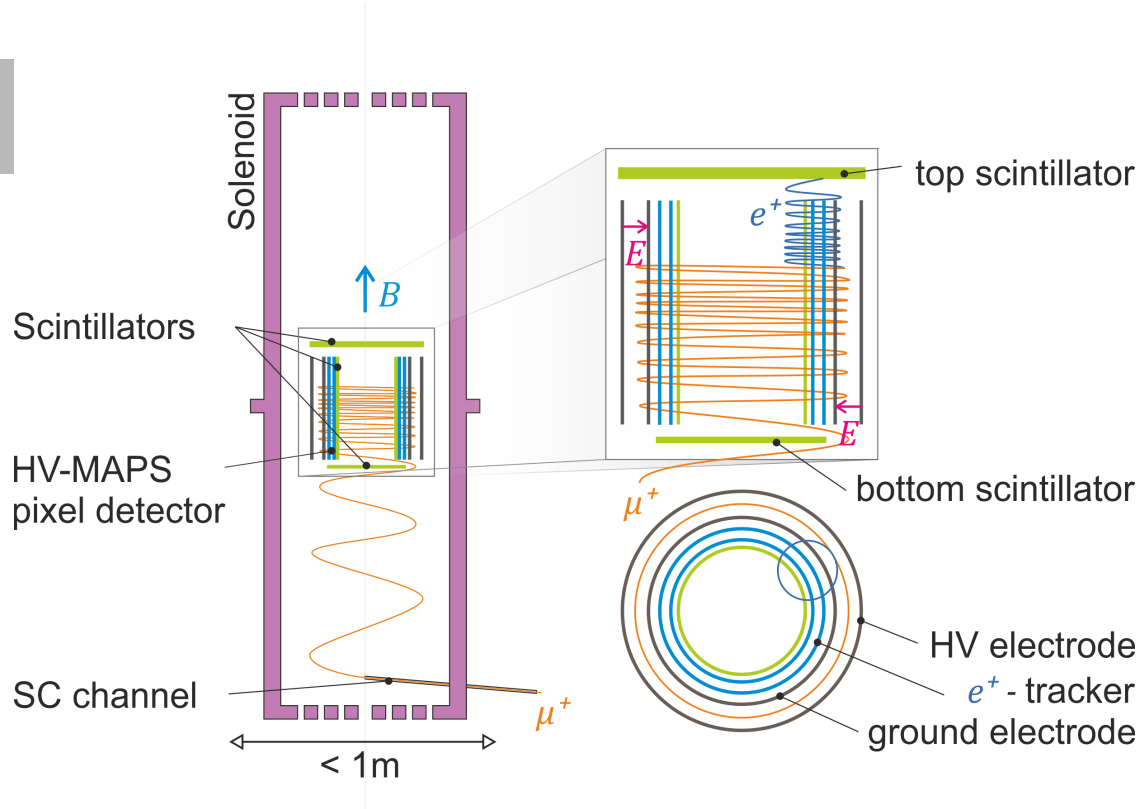
- Losses due to multiple passages through matter
- Losses due to multiple passage through low field area at exit of injection channel







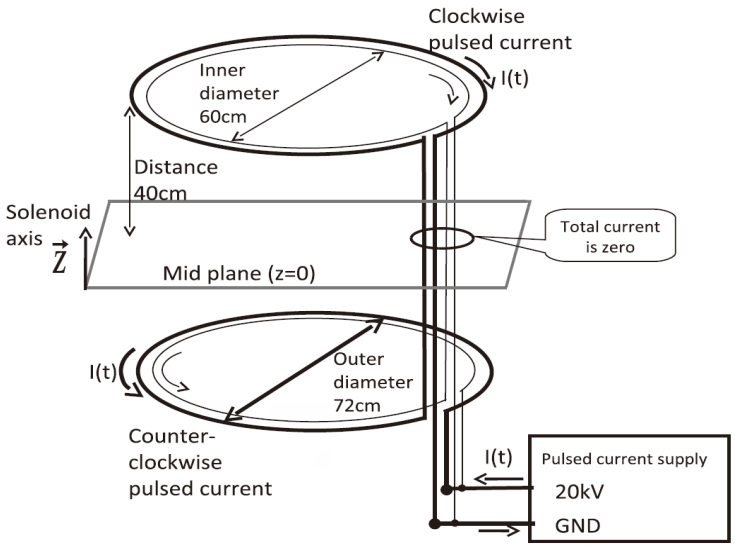
Frozen spin muEDM search with vertical injection

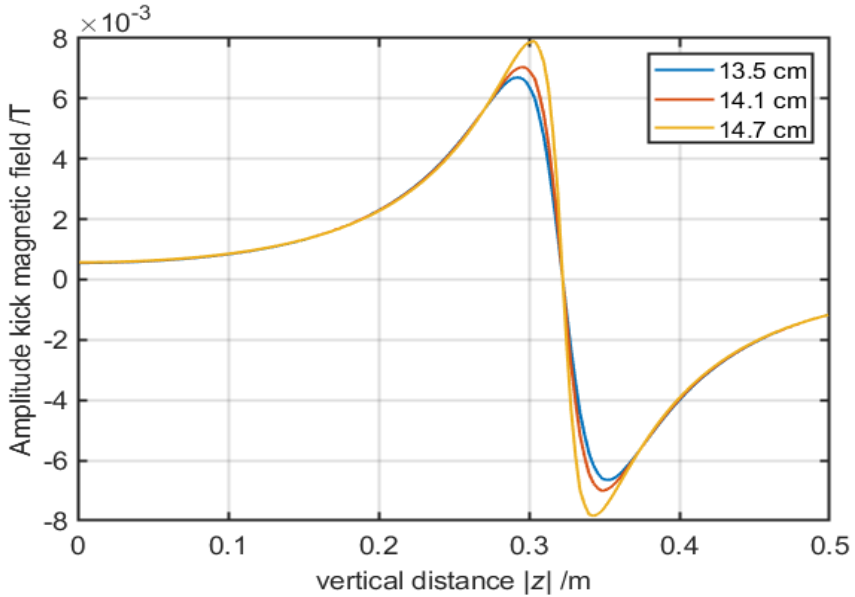


Helix muEDM

- 3D injection into uniform 3T-field
- Fast scintillator trigger in superconducting channel
- Trigger to kick time >50ns
- Radial magnetic field pulse
- Electrodes far away from injection
- Muon enters from top, no passage through electrodes
- Muon tagger for track ID
- Weak focusing field
- Single muon per storage
- HV-MAPS positron tracking
- Scintillator for fast “End” signal

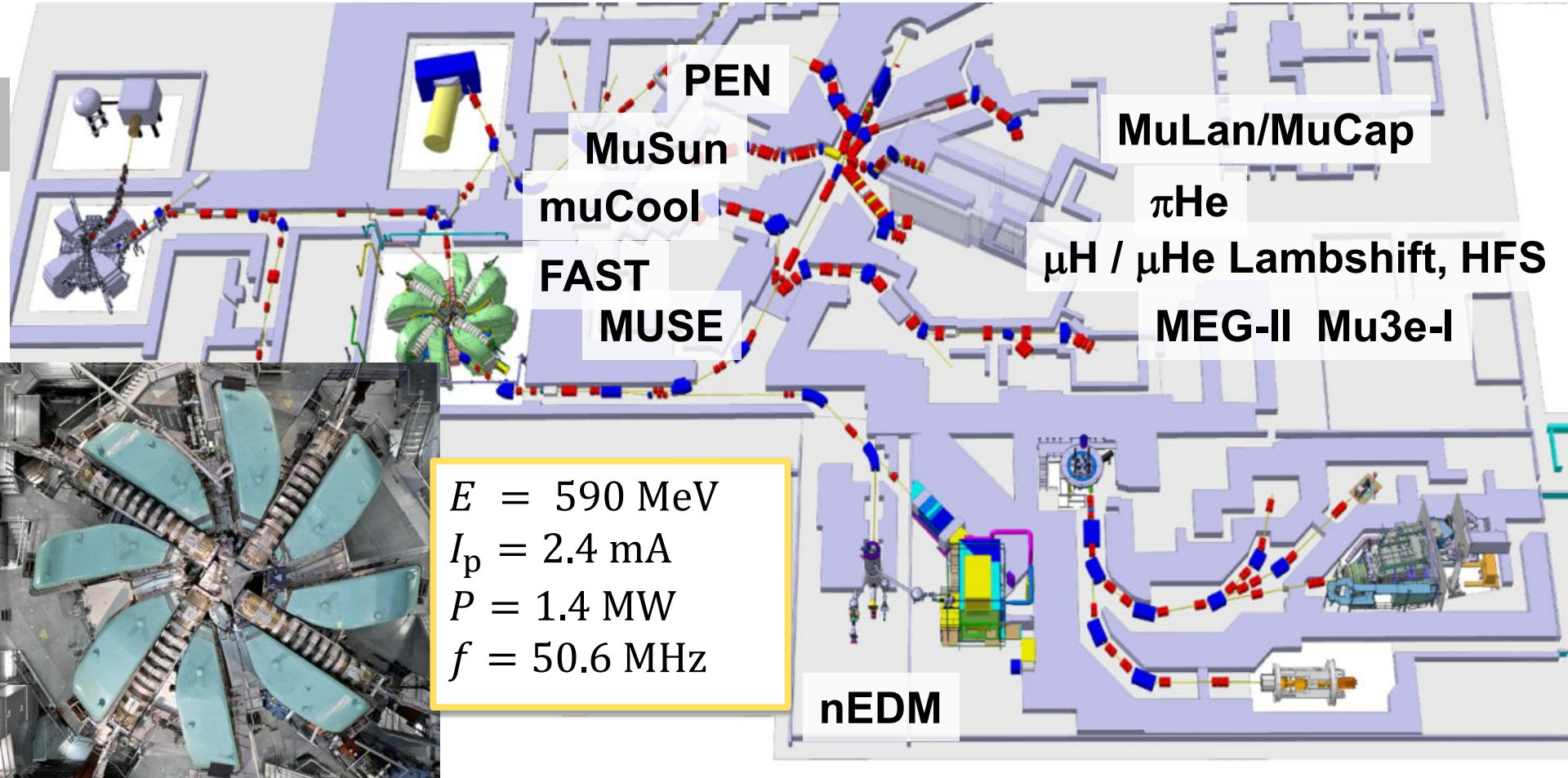
Radial magnetic field puls to kick muons



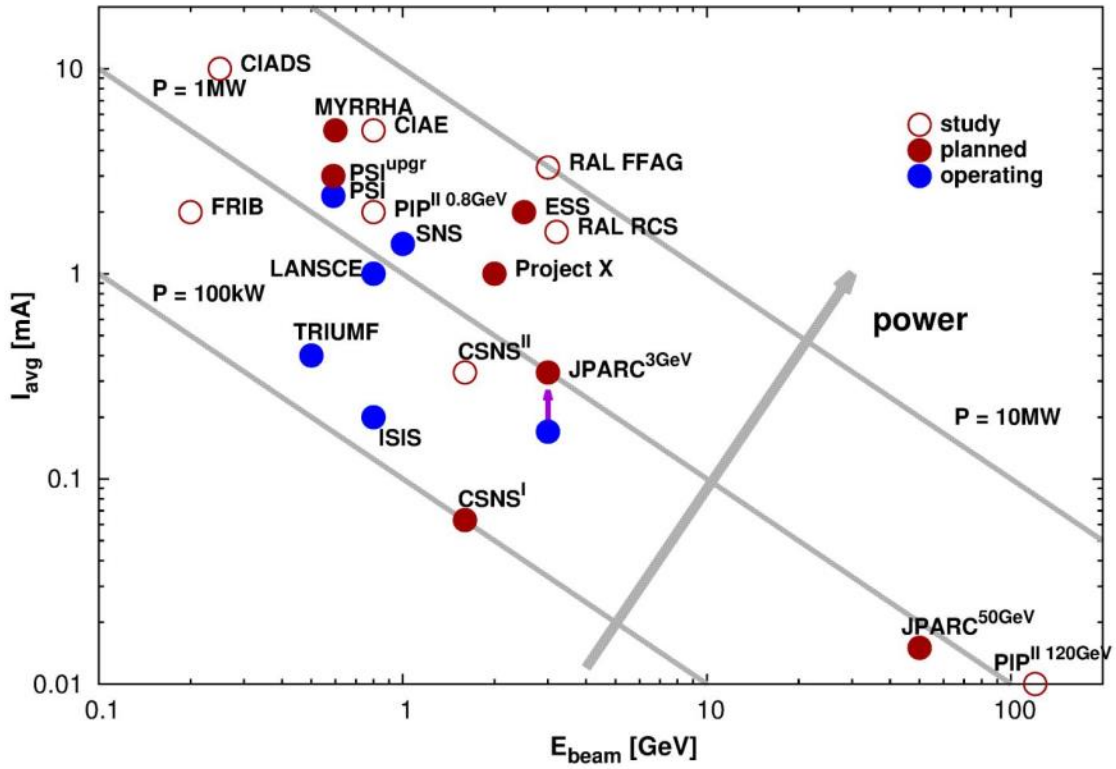


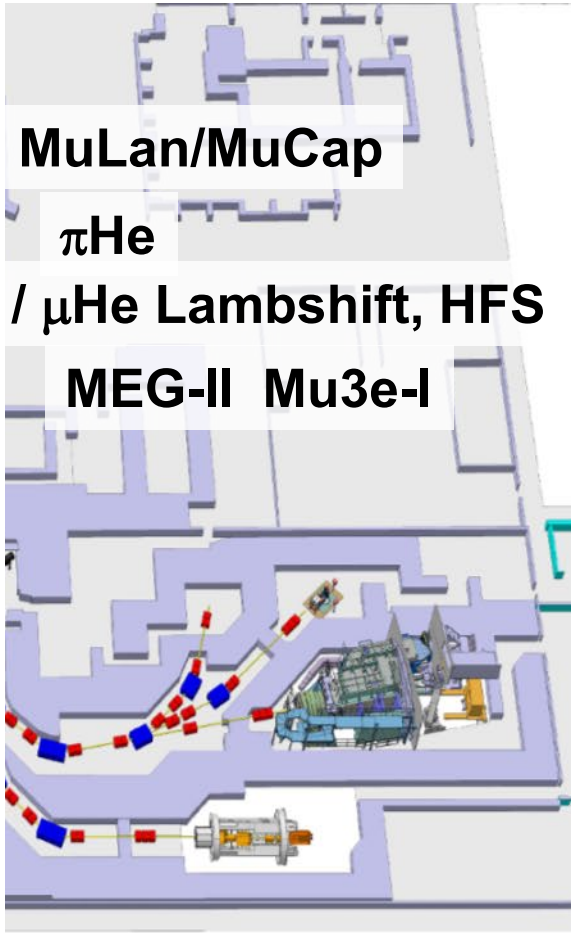
H. Iinuma *et al.,* NIMA832(2016)

HIPA -The proton accelerator facility at PSI



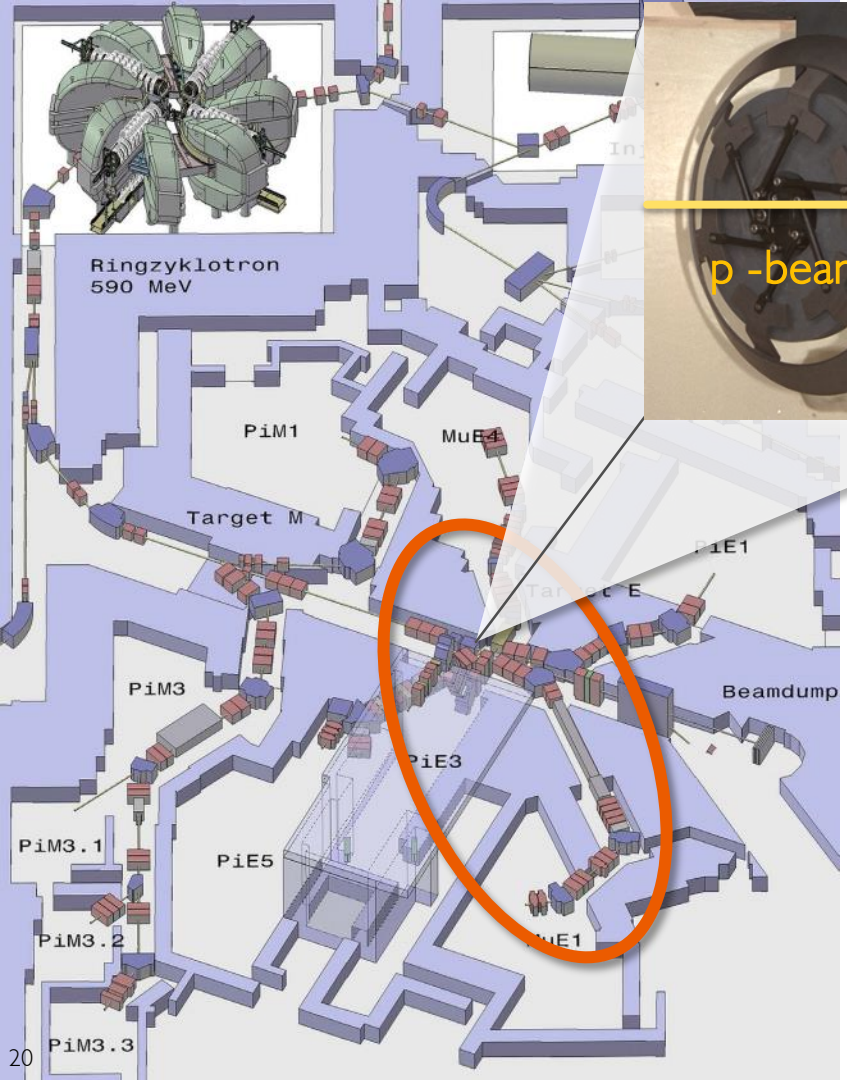
HIPA -The proton accelerator facility at PSI

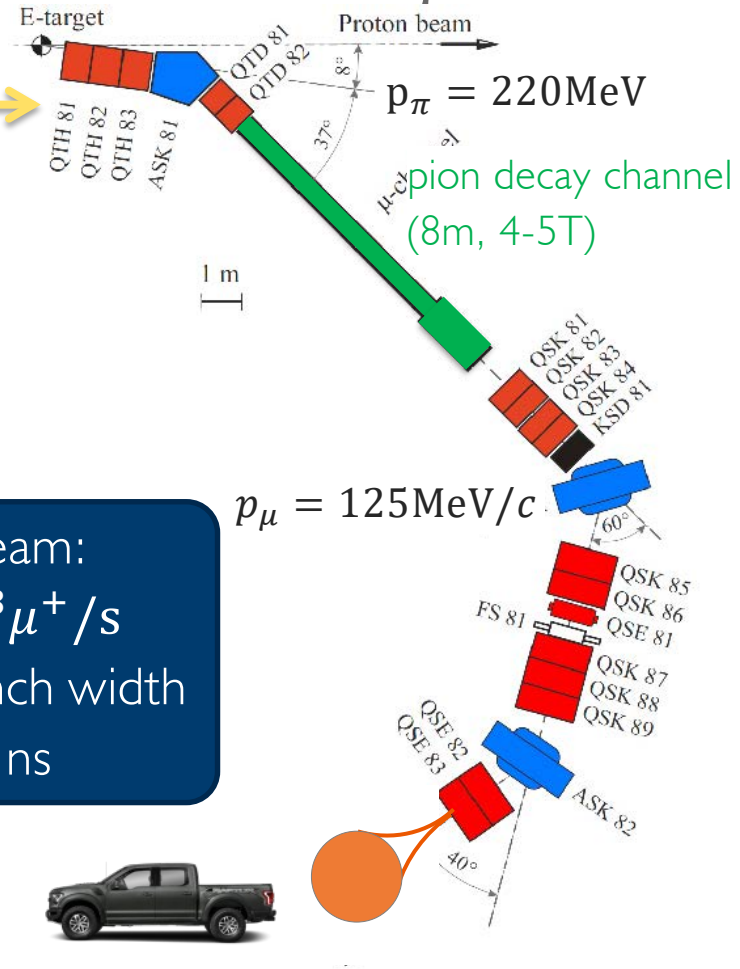




courtesy: M. Seidel

A search for a μEDM at PSI





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

pion decay channel
(8m, 4-5T)

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

μ-beam:
- $10^8 \mu^+/s$
- Bunch width 3.9 ns

Beam line characteristics

πE1 @ 28 MeV/c

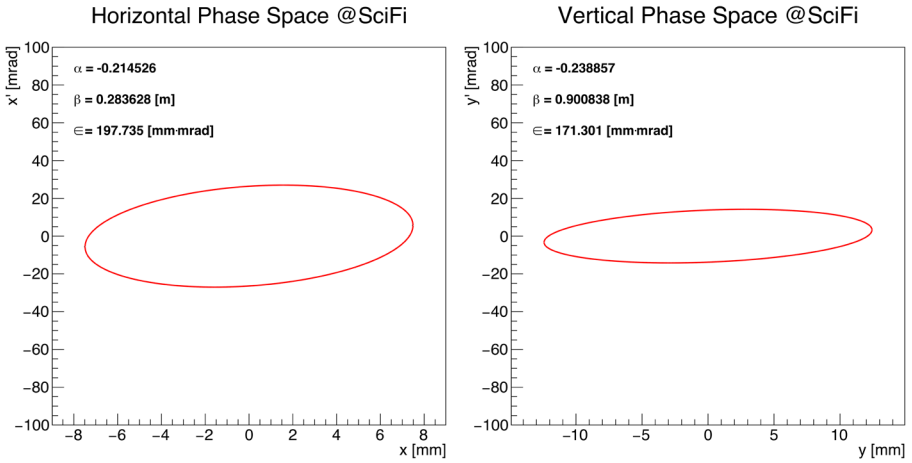
- Rate up to $3 \times 10^6 \mu^+/s$
- Emittance
  H: $195.2\ \mathrm{mm \cdot mrad}$
  V: $183.2\ \mathrm{mm \cdot mrad}$
- $P \approx 93\%$

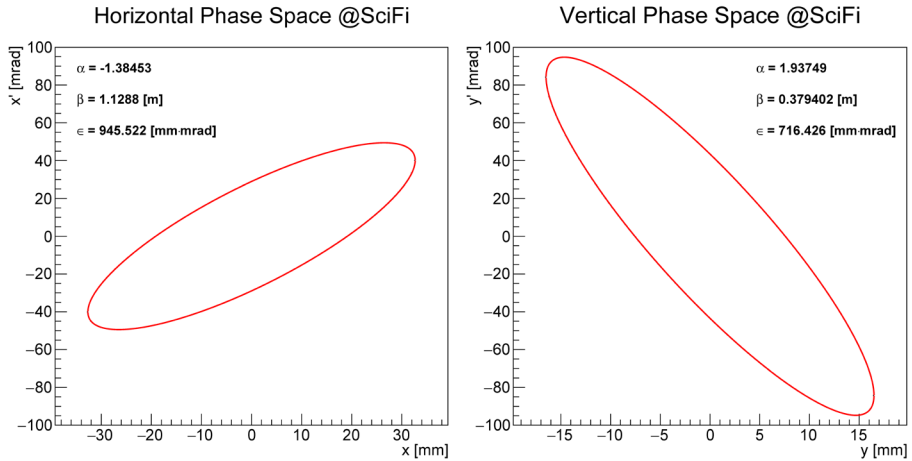
Tests, R&D and 1st data at low field 0.7T

μE1 @ 125 MeV/c

- Rate up to $2 \times 10^8 \mu^+/s$
- Emittance:
  H: $955\ \mathrm{mm \cdot mrad}$
  V: $716\ \mathrm{mm \cdot mrad}$
- $P \approx 93\%$

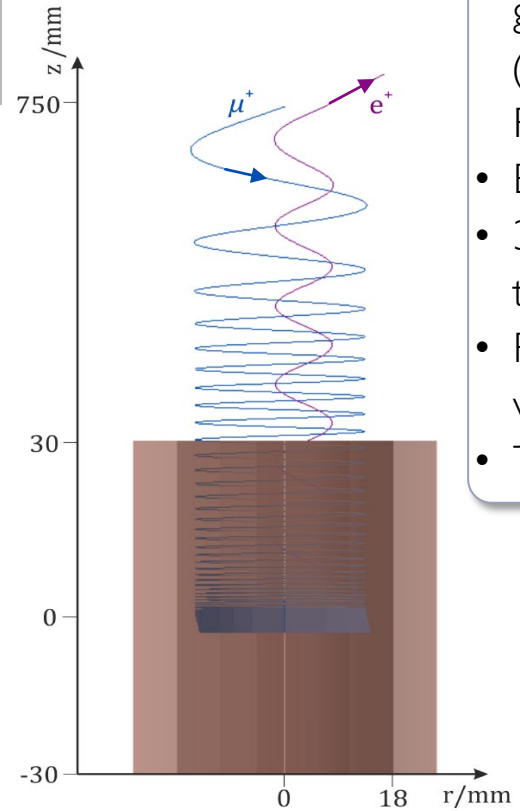
Final data taking at 3T

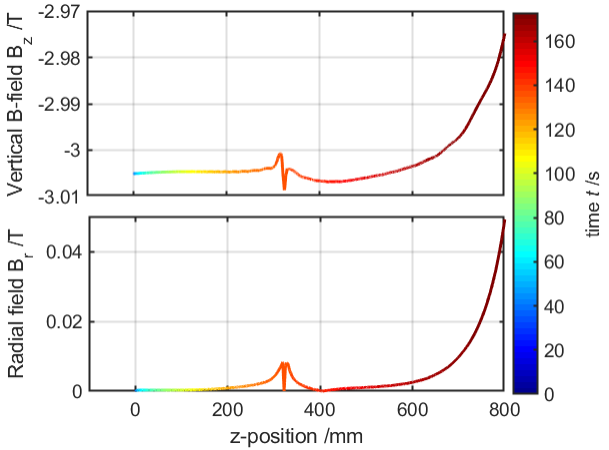


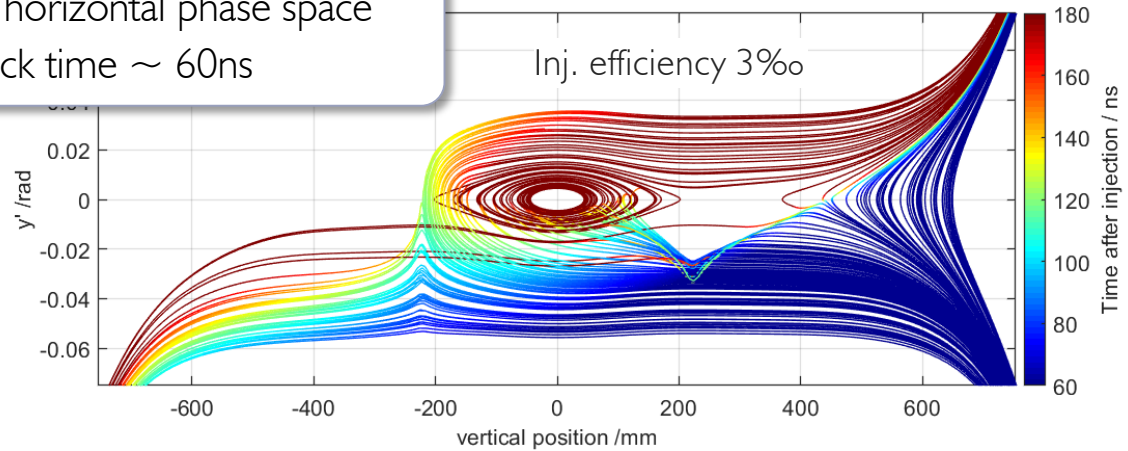


Simulation and injection efficiency

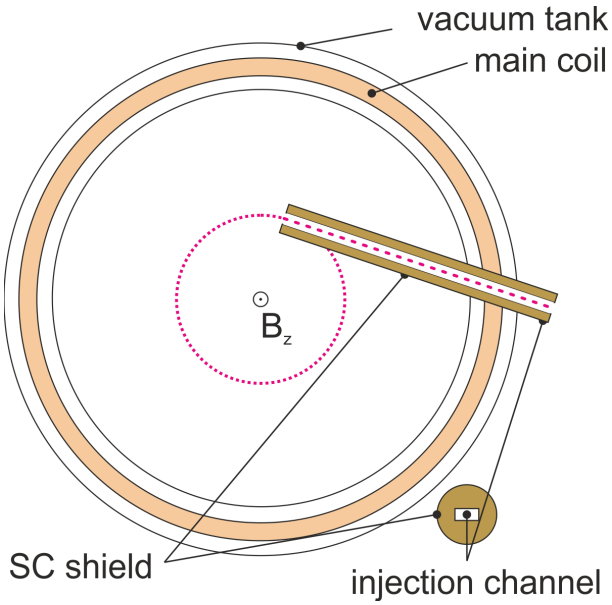
- Vertical dispersion sensitive to field gradient
  (magnetic adiabatic collimation)
  FEM optimization of magnetic field
- Electrodes out of the way
- 3 times better injection efficiency as in the lateral case
- Possible improvement by coupling vertical and horizontal phase space
- Trigger to kick time ~ 60ns

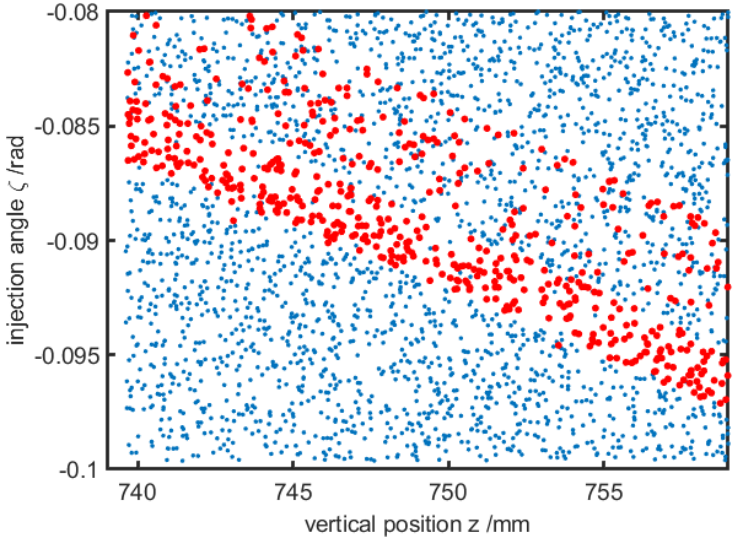


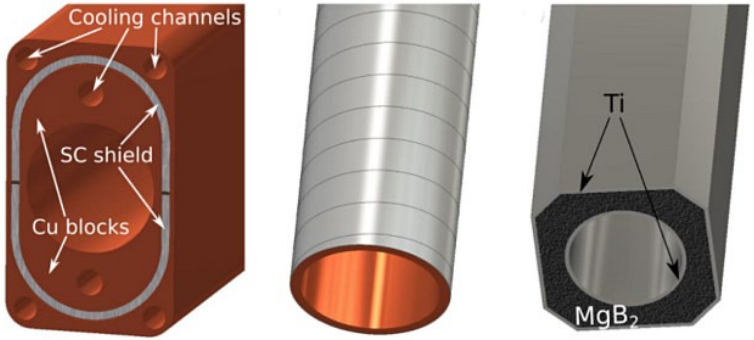




Injection channel







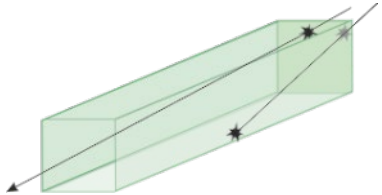
- Injection channel with SC magnetic shield
- Defined vertical and horizontal divergence

D. Barna et al., PR Acc. B 20 (2017) 041002
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4900108.
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4101310.

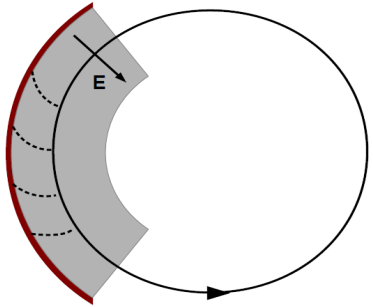
Muon tagging and positron tracking

Entrance trigger/tagger

- Trigger required for magnetic kick
  - Combination of scintillator signals (anti-coincidence) and machine frequency

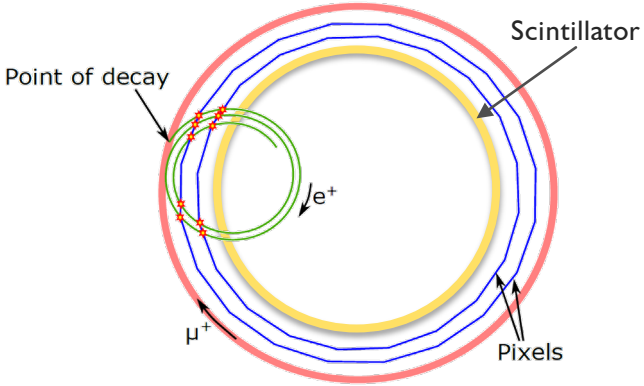


- Tagger
  - Muon track information for reconstruction of decay vertex

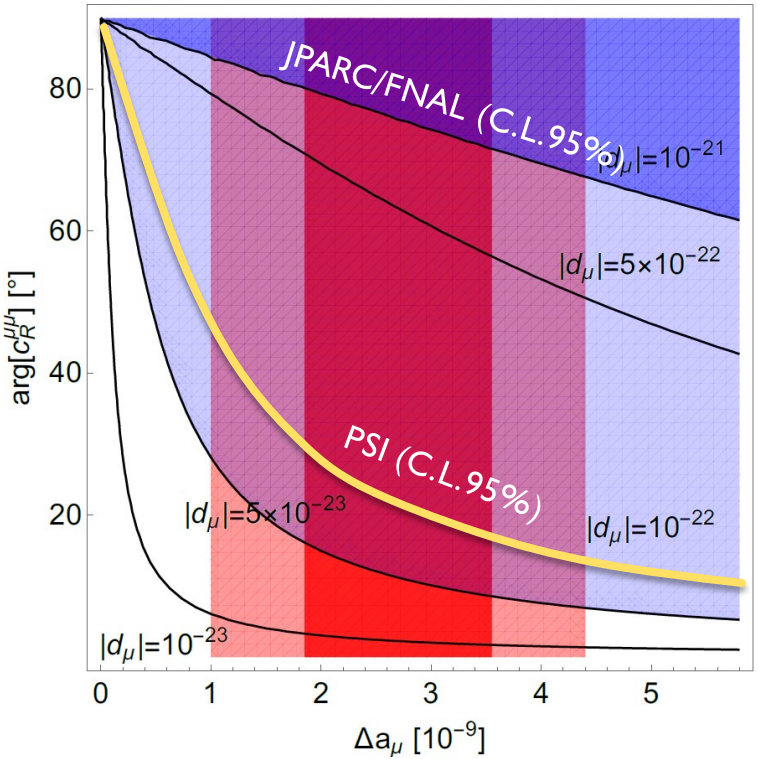


Positron tracker

- Barrel detector made of pixelated HV Maps silicon sensors (same technology as mu3e)
- Fast exit signal by scintillator (e.g. fibers) to lift veto for entrance



Sensitivity of helix muon EDM



Gamma factor ($p_\mu = 125\text{MeV}/c$)	γ	1.77
Initial polarization	P	0.93
Electric field ($B = 3T$)	E_f	2MV/m
Detection rate		60kHz
Mean decay asymmetry	α	0.3
Detections (200days)	N	10^{12}
$\sigma = \hbar\gamma a_\mu / \left(2PE_\text{f}\sqrt{N}\tau_\mu\alpha\right)$	$<$	6×10^{-23} $e$cm

Leptoquarks: A. Djouadi ZPhysC(1989), E.C. Leskow PRD95(2017), A. Crivellin arXiv:2010.06593, I. Doršner PRD102(2020), G. Hiller PRD102(2020)
New Scalars and Fermions: R. Dermisek PRD88(2013), S. Raby PRD97(2017), K. Kowalska arXiv:2012.15200, M. Endo JHEP08(2020), J. Kawamura PRD100(2019)
MSSM: G.Hiller PRD82(2010)

HIMB & MuCOOL phase:
Decay rate probably a factor 100 higher, if prospected beam size (1mm) and divergence (sub mrad) can be maintained in re-acceleration.

Systematic effects due to imperfections

Possible effects

- Radial magnetic field B_r
- Magnetic "plane" does not coincide with Electric "plane"
- Electric field not in one plane
- Different detector efficiencies (spatial or time variations)
- …
- …

Remedies

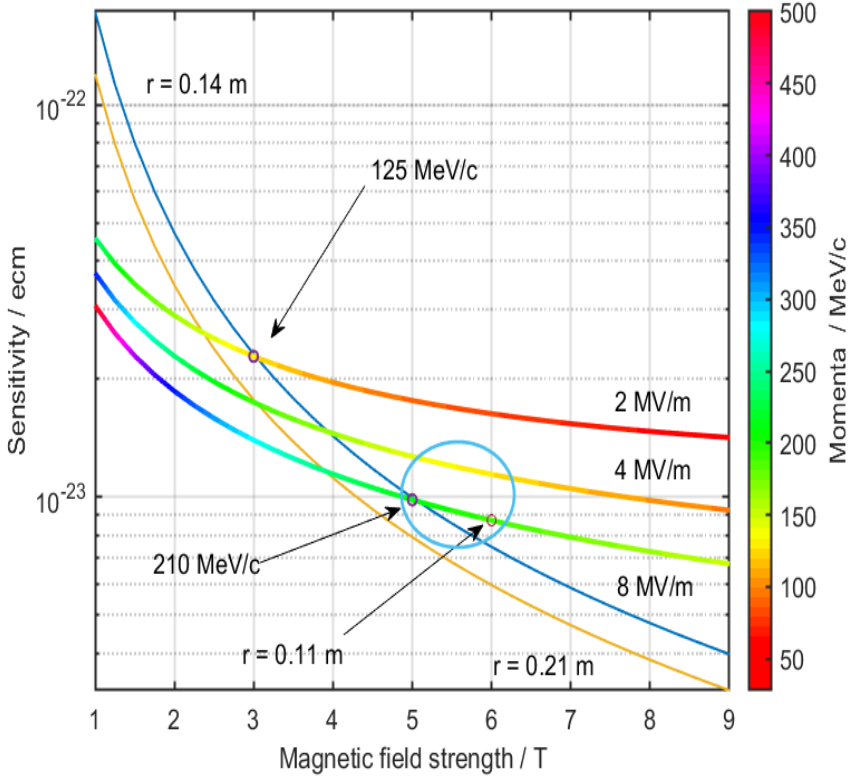
- Clock and counter clockwise injection (cancels most effects)
- Time binning of positron tracks over multiples of one period ($\sim 4\text{ns}$)
- … work in progress

Farley *et al.*, PRL93(2004)

Prospects at a high intensity muon beam line

HIMB project at PSI

- New surface beam:
  up to $10^{10}\mu^+/s$ polarized
- **MuCool** cold muon source
  keep high polarization
  - $5 \times 10^5 \mu^+/s$
  - $E = 10\ \mathrm{keV}$
  - $\epsilon \ll 1\ \mathrm{mm\ mrad}$
- Re-acceleration keeping
  low emittance



Conclusion

- The search for the muon electric dipole moment is a unique venue to explore CP-violation in BSM physics
- A search of a muon EDM complements current EDM searches by testing CPV in a second generation lepton, clean of nuclear and atomic background
- This letter of intent proposes to measure the muon EDM using the frozen spin technique in a compact solenoid field at PSI
- A sensitivity of better than

$$d_\mu < 6 \times 10^{-23} e\text{cm}$$

  is expected using existing beamlines
- With the advent of HIMB and muCool an even higher sensitivity is likely in a second phase of the search

The muEDM – (proto)collaboration

A. Adelmann,[1,2] M. Backhaus,[1] C. Chavez Barajas,[3] N. Berger,[4] T. Bowcock,[3] A. Bravar,[5] C. Calzolaio,[2] L. Caminada,[2,6] G. Cavoto,[7] R. Chislett,[9] A. Crivellin,[2,6,10] M. Daum,[2] M. Fertl,[11] M. Giovannozzi,[10] W.C. Griffith,[12] G. Hiller,[13] G. Hesketh,[9] M. Hildebrandt,[2] I. Keshelashvili,[14] A. Keshavarzi,[14] K.S. Khaw,[16,17] K. Kirch,[1,2] A. Kozlinsky,[4] A. Knecht,[2] M. Lancaster,[15] B. Märkisch,[18] F. Meier Aeschbacher,[2] F. Méot,[19] A. Nass,[114] A. Papa,[2,20] J. Pretz,[14,21] J. Price,[3] F. Rathmann,[14] F. Renga,[7,8] M. Sakurai,[1] P. Schmidt-Wellenburg,[2] A. Schöning,[22] M. Schott,[4,11] C. Voena,[7,8] J. Vossebeld,[3] F. Wauters,[4] and P. Winter[23]

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13 technische universität dortmund
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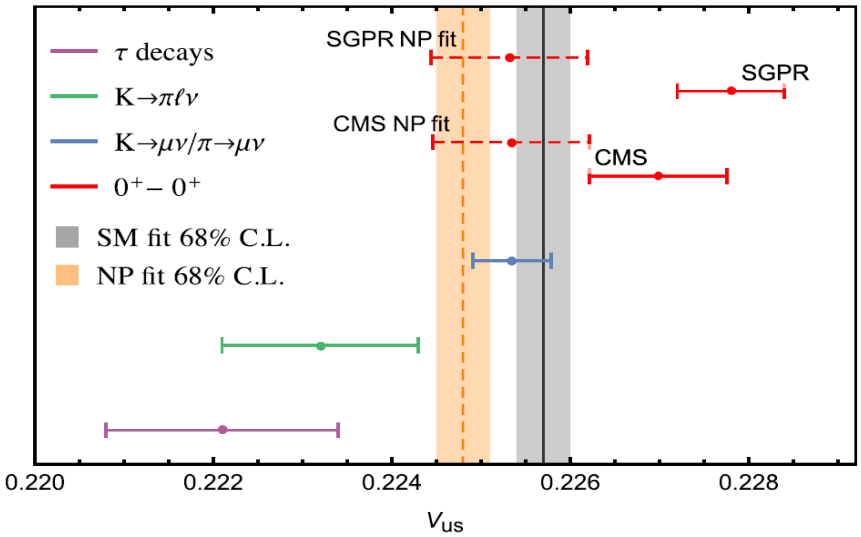
16 SHANGHAI JIAO TONG UNIVERSITY
17 Tsung-Dao Lee Institute
18 TUM
19 BROOKHAVEN NATIONAL LABORATORY "a passion for discovery"
20 UNIVERSITÀ DI PISA
21 RWTH AACHEN UNIVERSITY
22 UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
23 Argonne NATIONAL LABORATORY

Backup

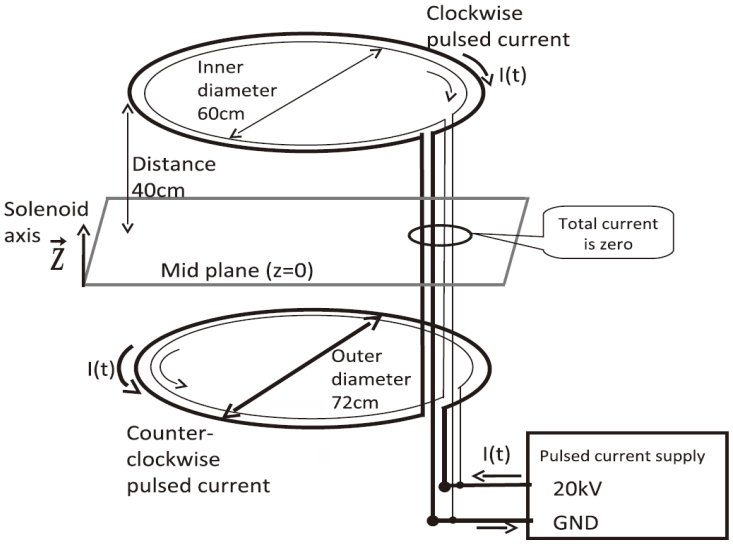
Cabibbo-angle anomaly

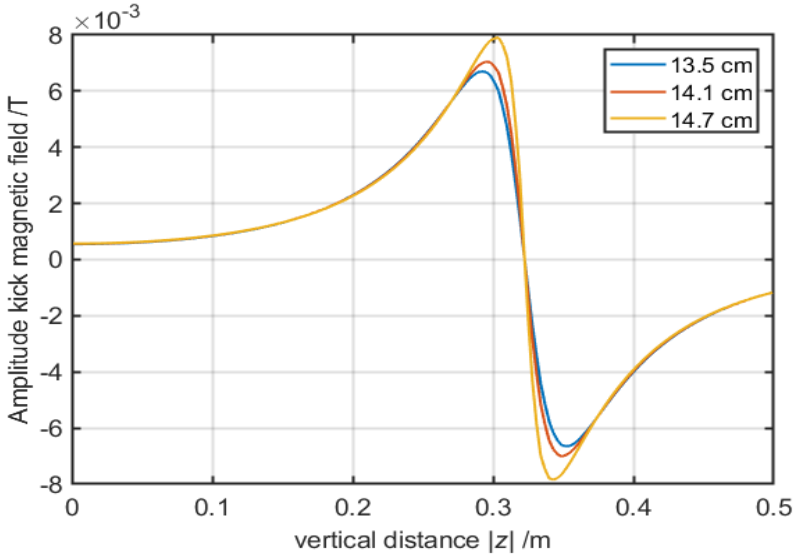


- V_{us} from τ-decays and from K-decays do not agree
- $\sim 3\sigma$ tension with V_{us} from super-allowed β-decays using SM CKM unitarity
-

A.M. Coutinho *et al.*, PRL 125(2020)071802

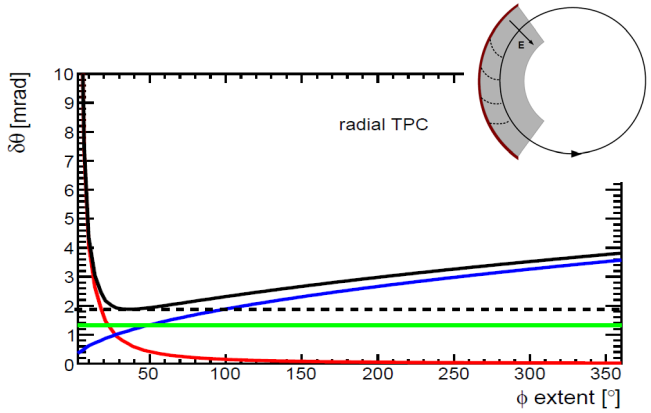
Magnetic field kicker

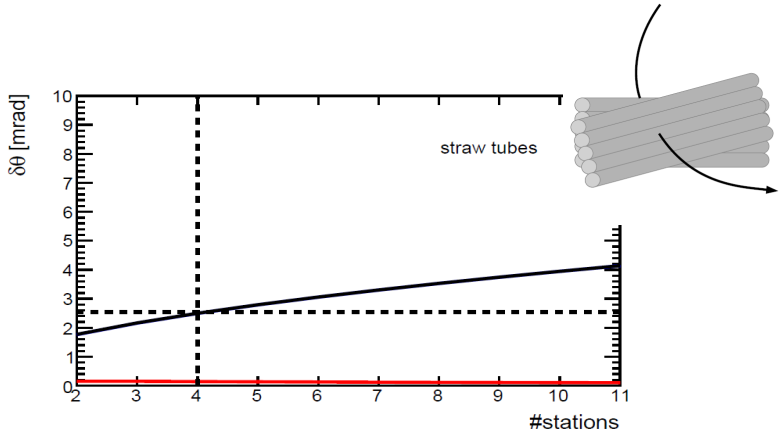


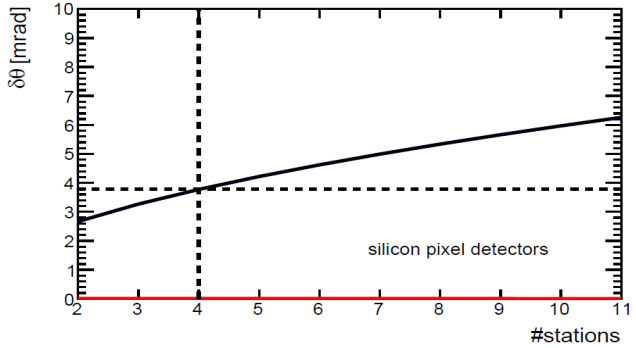


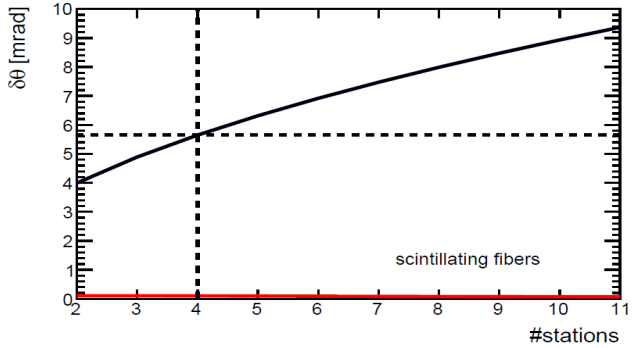
H. Iinuma *et al.,* NIMA832(2016)

Muon Tagger study

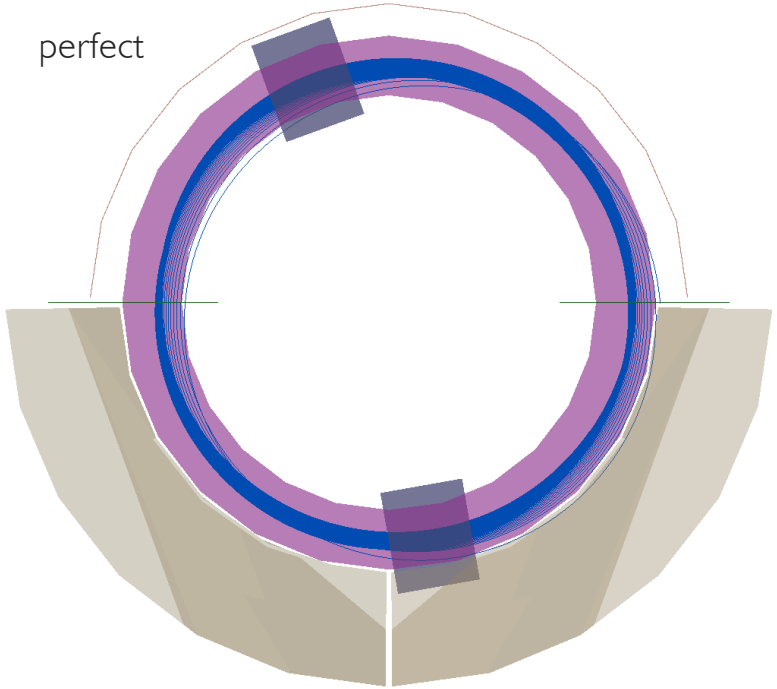








Simulation and injection efficiency

Lateral injection

- Perfect lateral injection is possible in a homogenous field with an efficiency of better than 97%
- Once real features are added, low field region for injection and material for electrodes and injection channel efficiency drops to about 7%