# Search for the electric dipole moment of the muon at PSI

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15 TUM
16 BROOKHAVEN NATIONAL LABORATORY "a passion for discovery"
17 UNIVERSITÀ DI PISA
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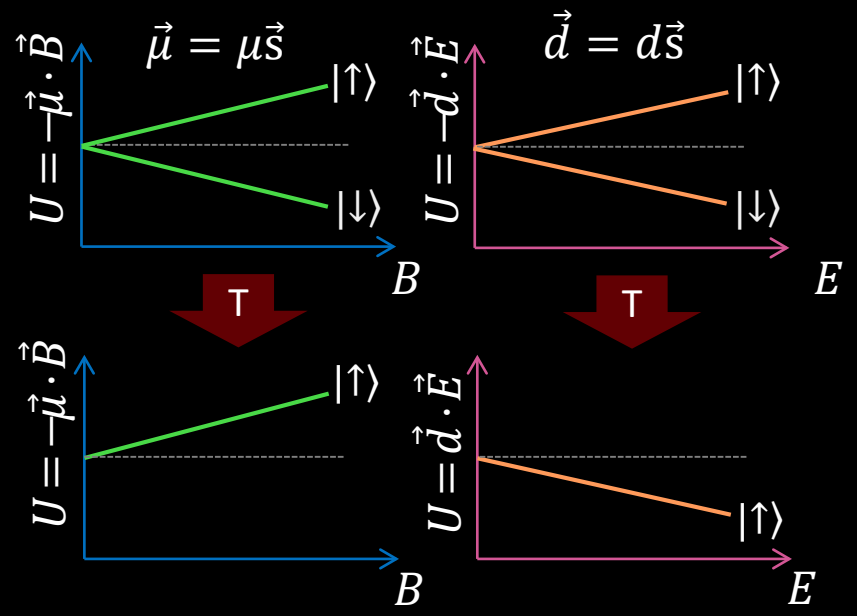
# CP violation & EDM

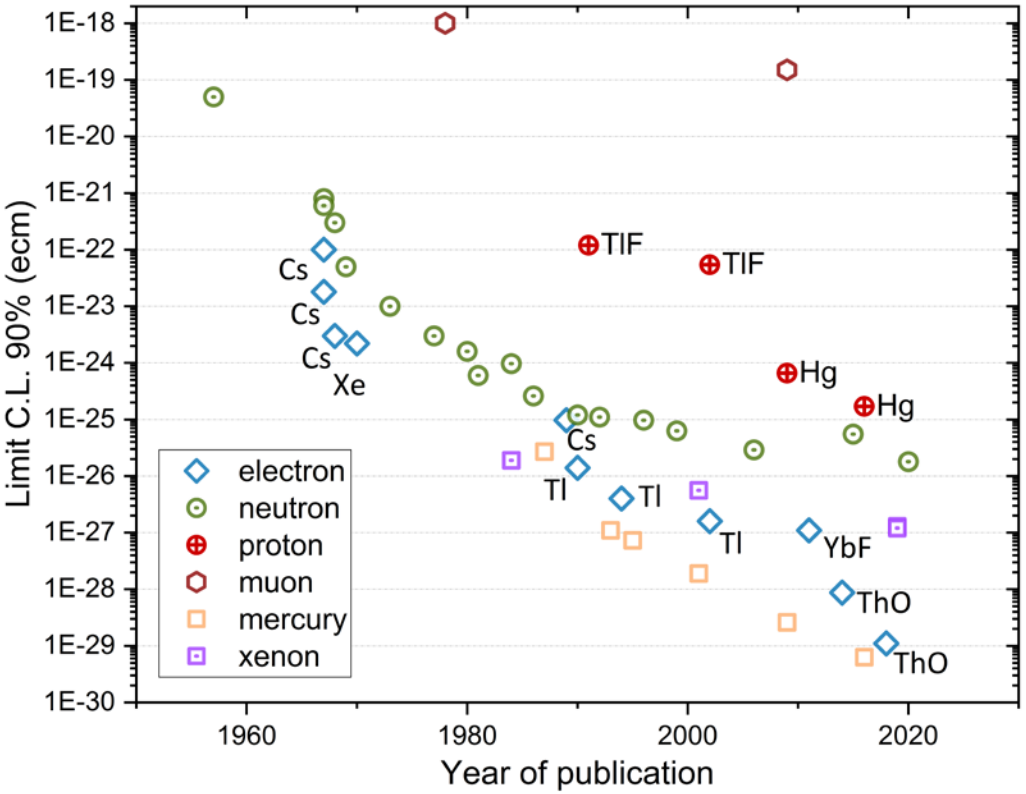


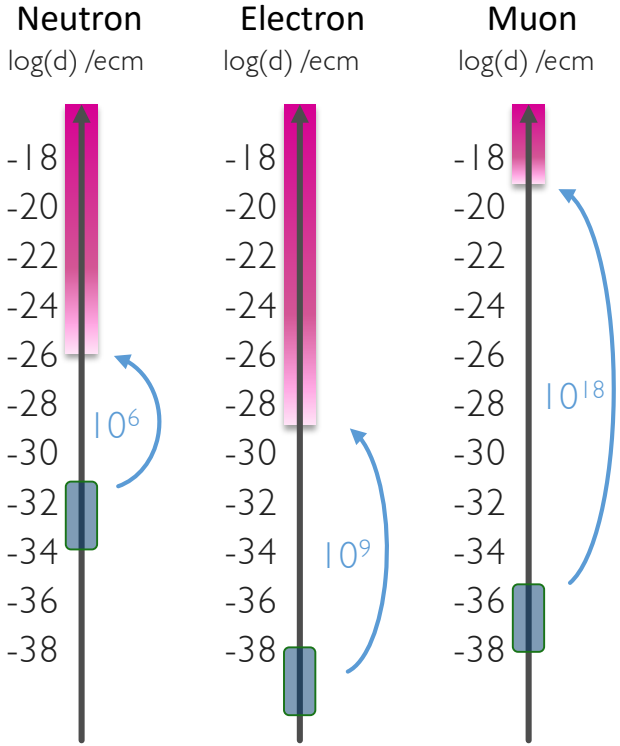

A non-zero particle EDM violates P, T and, assuming CPT conservation, also CP.

EDM ⟺ CPV

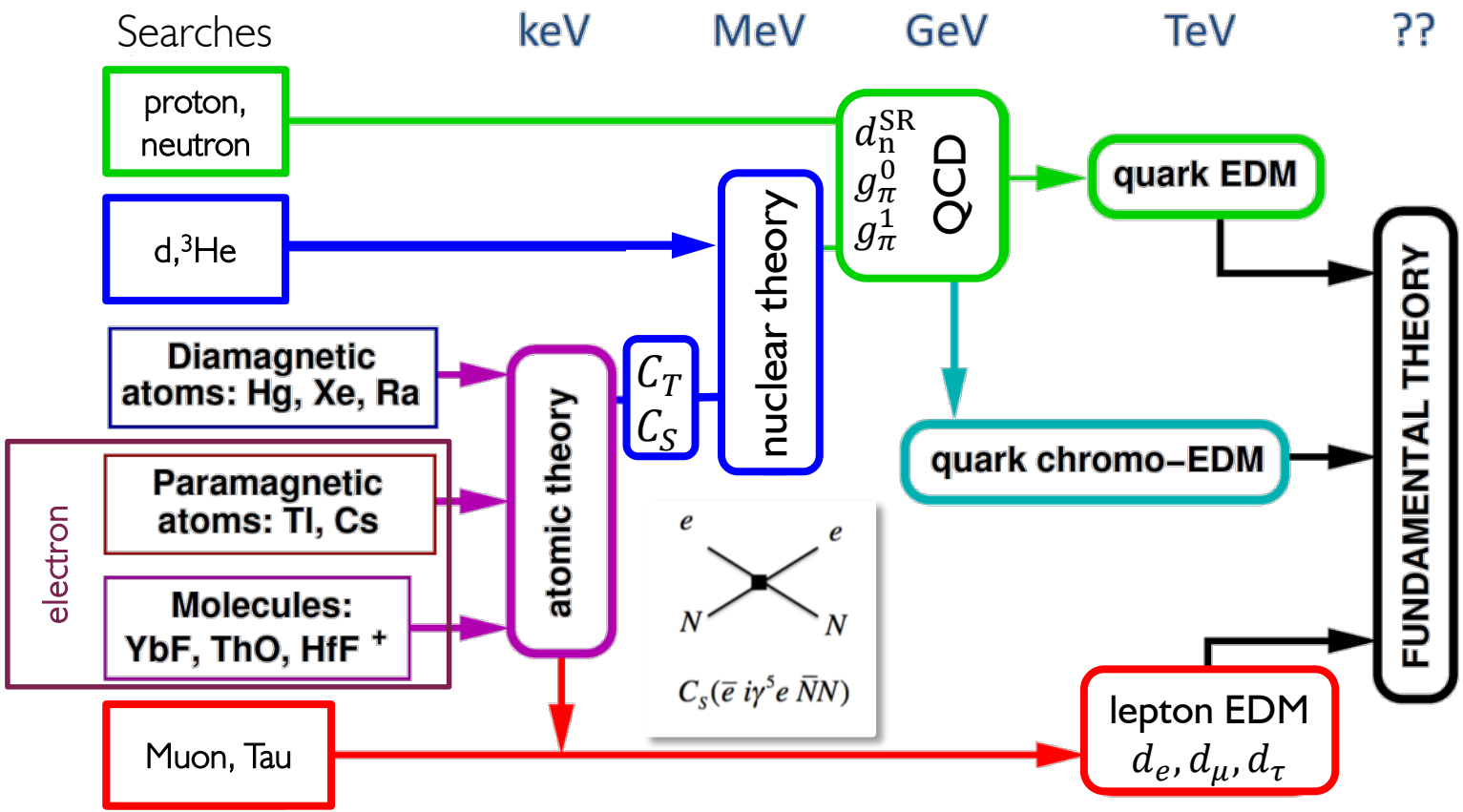
- Baryon asymmetry of the Universe
- Arises "naturally" in beyond SM theories
- Strong CP violation ($\theta$-term)

# A brief history of EDM searches



# 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

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

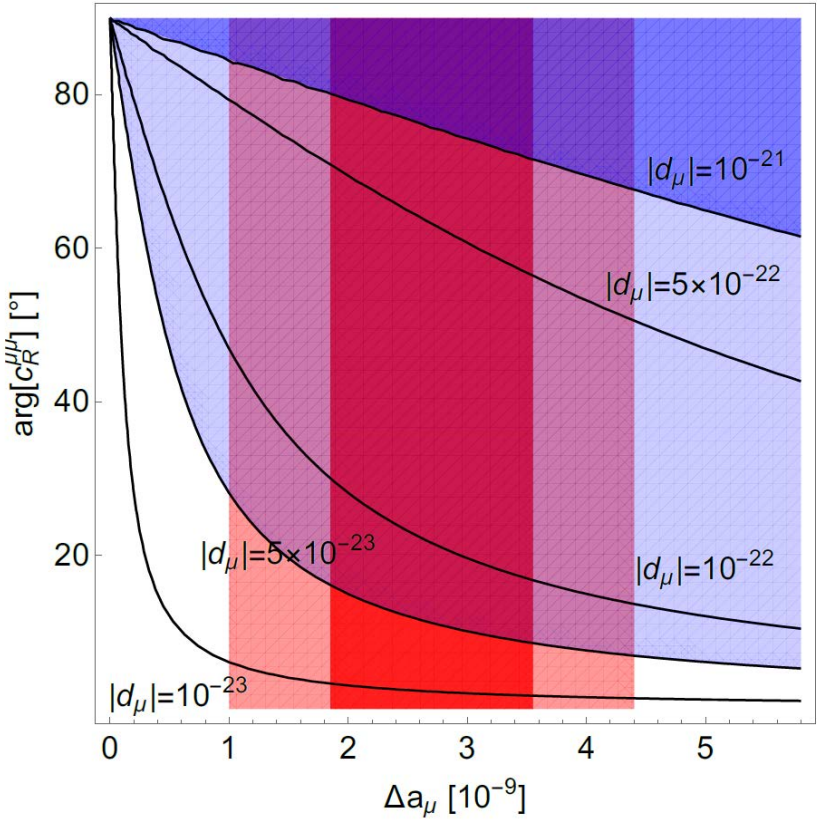
charge

electric-dipole

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

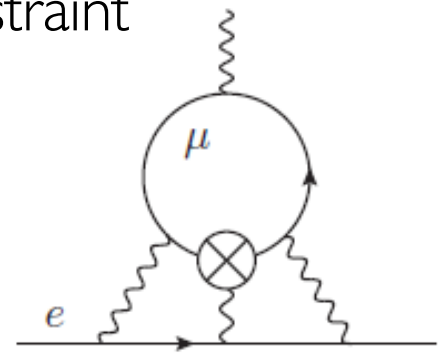
$$F_3 = d_{l_i} = i \left( c_R^{l_i l_i} - c_R^{l_i l_i *} \right) = -2 \text{Im}\, c_R^{l_i l_i}$$

# Limits on $\mu$EDM in lepton flavor violating models



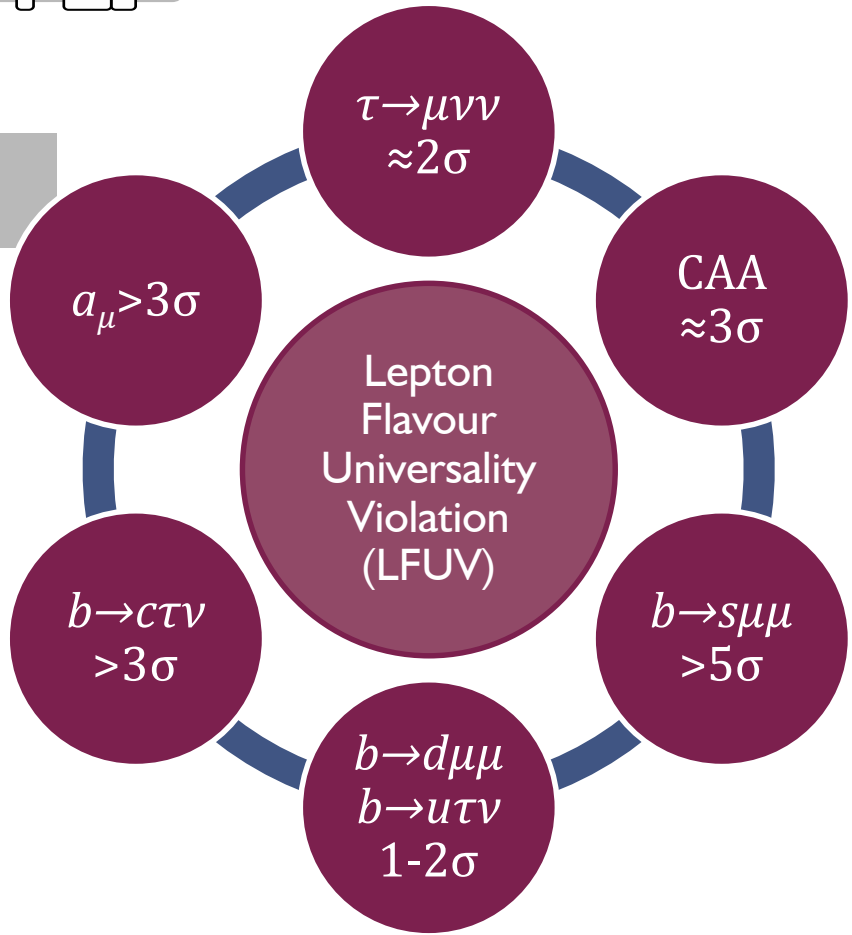

A.Crivellin, M. Hoferichter, PSW PRD 98(2018) 113002

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



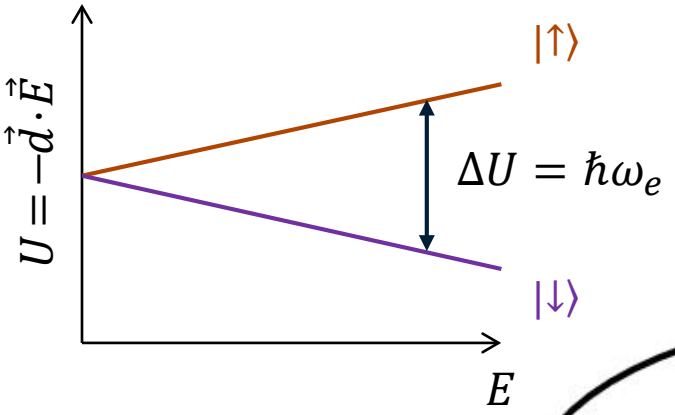

- $\mu$EDM contribution in electron EDM allows for large value: $d_\mu \leq 7.5 \times 10^{-19}\ e\mathrm{cm}$

# Hints of new physics



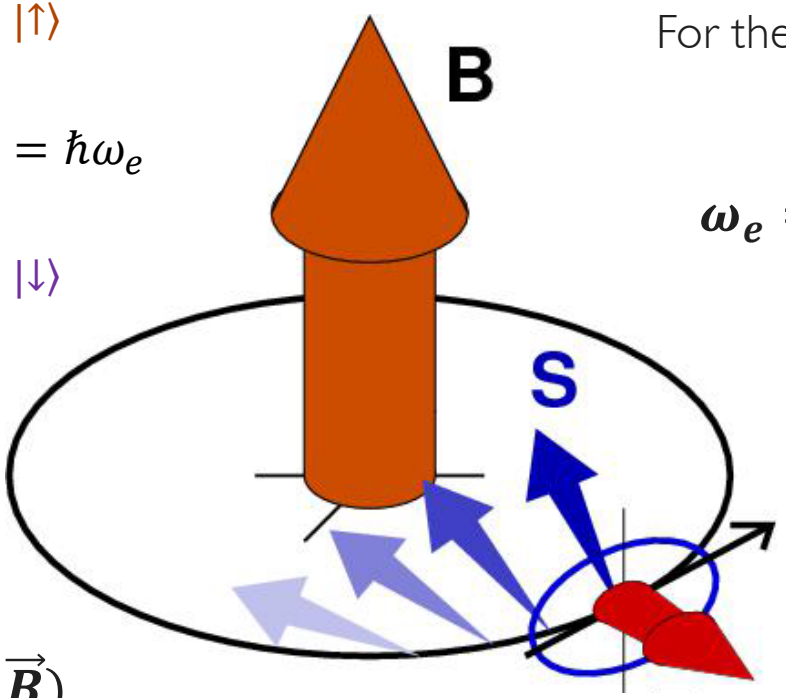

- Decay of B-mesons at LHC Babar and Belle deviate from SM expectation
- Tension in $\tau \to \mu\nu\nu$
- Cabibbo-angle anomaly might be a indication of LFUV
- Anomalous magnetic moment of muon deviates from SM

# A relativistic charged particle in a strong B-field




For the moment assume $\mu = 0$

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



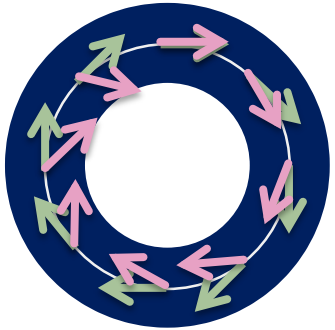

$$\vec{v} = \vec{\beta} c$$

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

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

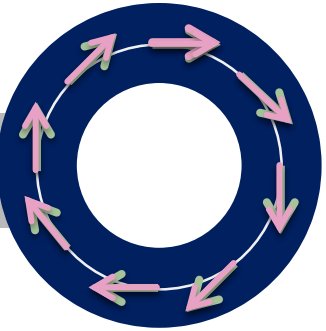
# Frozen spin technique for the muon EDM

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



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

# Frozen spin technique for the muon EDM



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

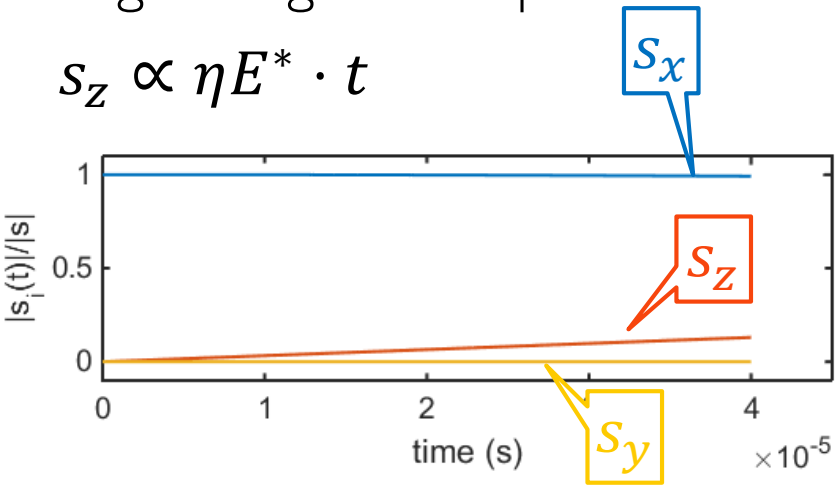
- Cancel anomalous precession with matched E-field:

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

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

- An EDM signal is visible as growing vertical polarization

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

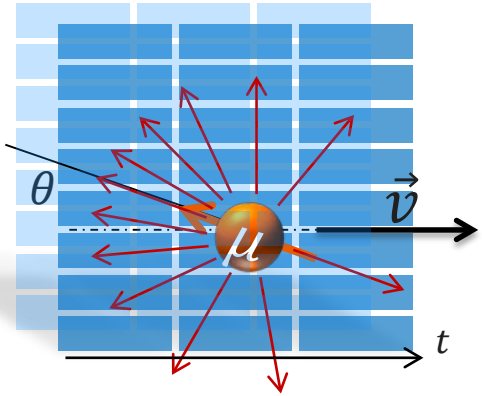


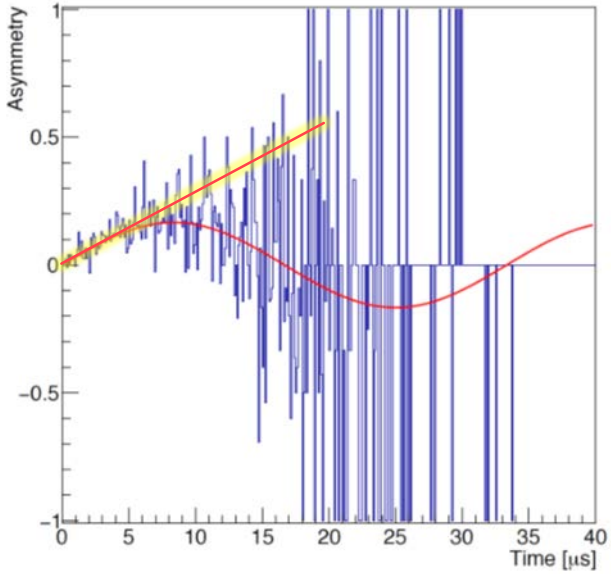

Farley *et al.*, PRL93(2004)
Adelmann *et al.*, JPG37(2010)

# 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 $a_\mu$-precession to tune $E_f \cong aBc\beta\gamma^2$

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




The slope gives the sensitivity of the measurement:

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

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

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

# Muon EDM kick off workshop at PSI 17.02-19.02.2020

## Kick-off workshop for the search of a muon EDM using the frozen spin technique at PSI

17-19 February 2020
Europe/Zurich timezone

- Overview
- Workshop Topics
- Scope of the Workshop
- List of invited speakers
- Call for Abstracts
- Agenda
- Timetable
- Contribution List
- Book of Abstracts
- Registration fee
- Registration
- Participant List
- Venue
- Accomodation

Mailing List: https://elog.psi.ch/elogs/Muon+EDM+Mailing+List/

Remote link: https://psi-ch.webex.com/psi-ch/j.php?MTID=mbb1db2d988c4d00d68ec5da10b33ad15 (Muon2020)

The aim of the workshop is to bring together scientists strongly motivated to participate in a search for a muon electric dipole moment (EDM) using the frozen spin technique at PSI.

The workshop will be organized as a topical seminar with break-out sessions addressing the different challenges of a compact muon storage ring employing the frozen spin technique to search for an electric dipole moment of the muon. In addition to invited contributions (30'), we very much appreciate shorter contributions by all participants. We plan for ample discussion time in each session.

Venue: PSI, West
Monday: WHGA 001 / Auditorium
Tuesday: WBGB 019
Wednesday: WBGB 019

**Starts** 17 Feb 2020, 09:00 PSI

## 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

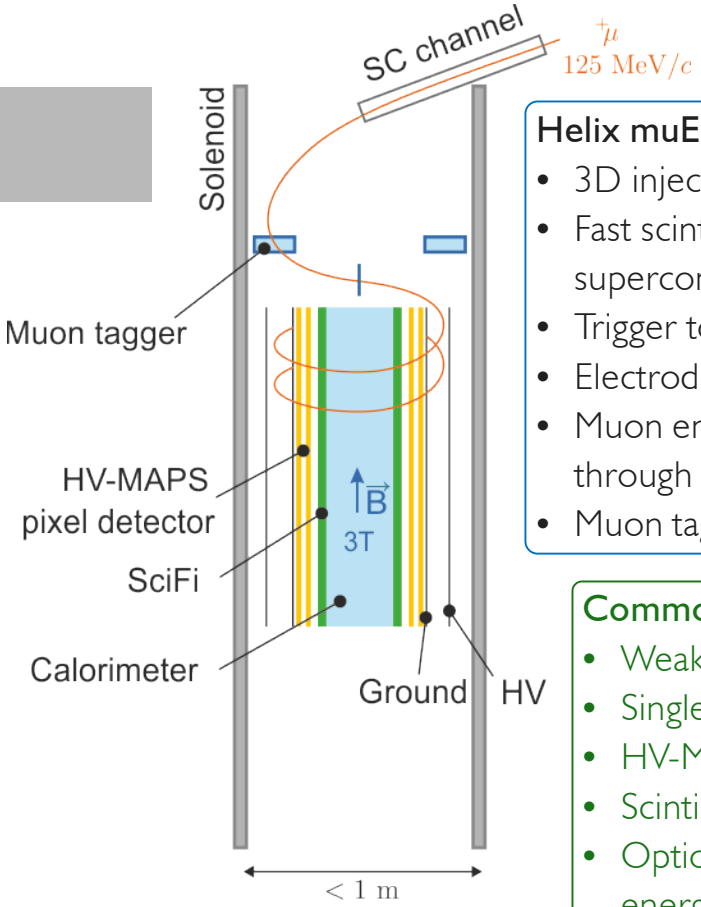
François Meot, Brookhaven National Laboratory

Angela Papa, University of Pisa

Frank Rathmann, Forschungszentrum Jülich

Peter Winter, Argonne National Lab

# Two concepts for a muon EDM at PSI



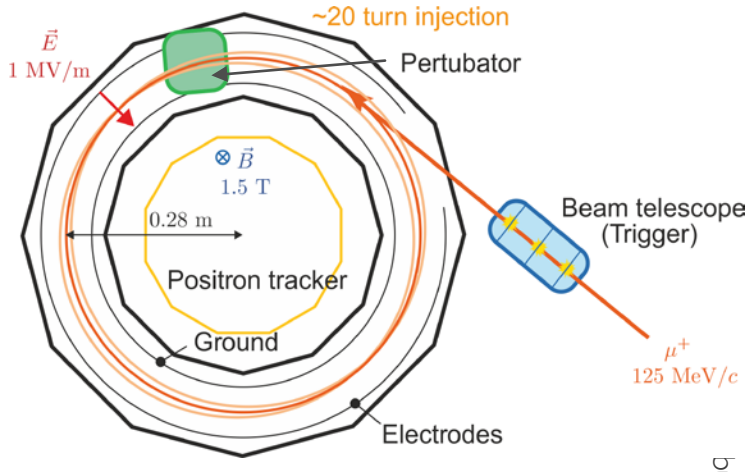

H. Iinuma *et al.*, NIMA832(2016)

## 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

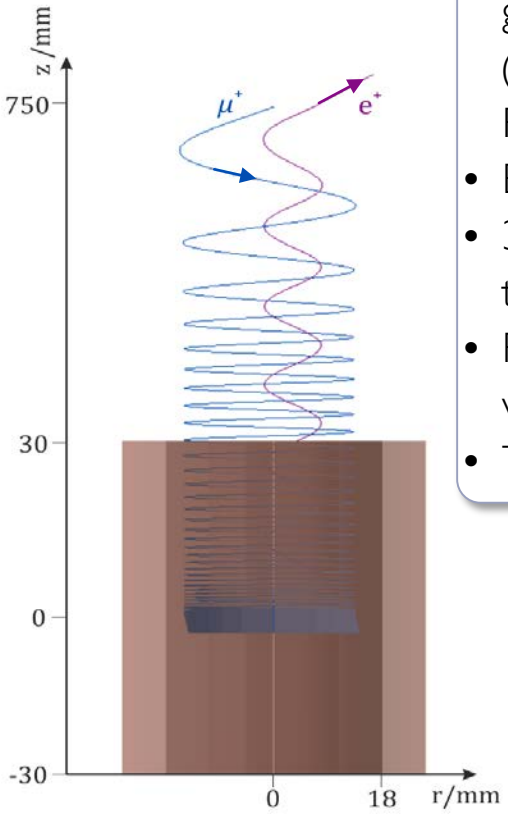



A. Adelmann *et al.*, JPG37(2010)

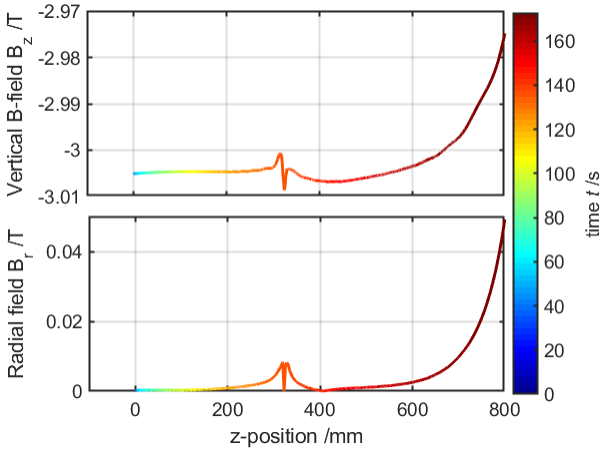
## Lateral muEDM storage ring

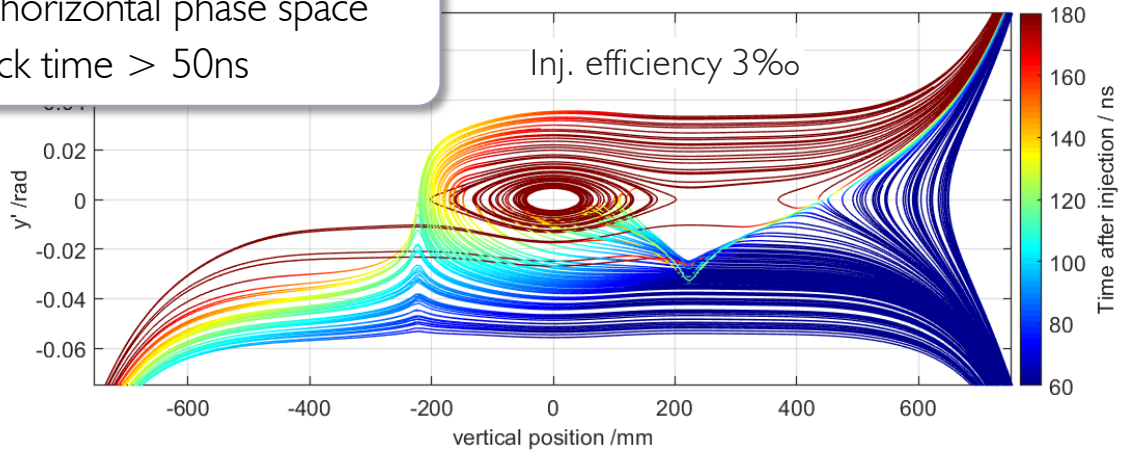
- Lateral injection into uniform 1.5T-field
- Fast scintillator trigger upstream in beamline
- Trigger to kick time <10ns
- Muon enter with multiple passages through electrodes/material (losses/scattering)
- Injection channel close to HV electrode
- Low field in injection zone perturbs injection

# 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 > 50ns



# Beam line characteristics

## $\pi$E1 @ 28 MeV/c

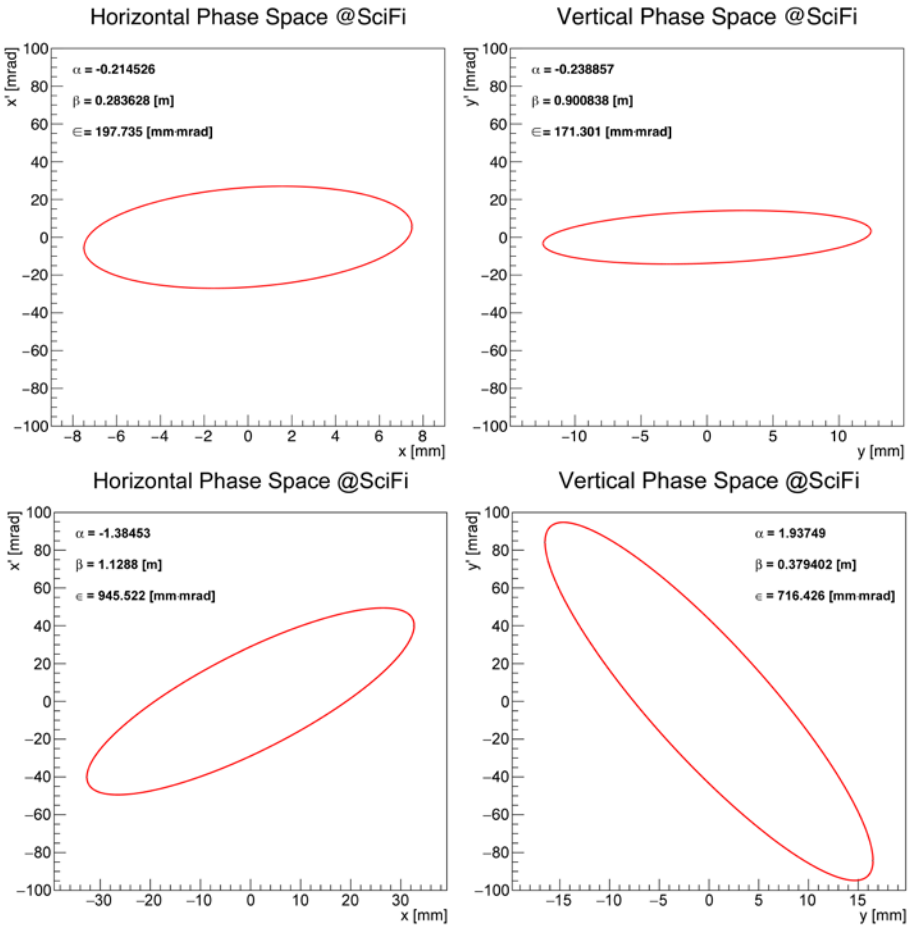
- Rate up to $3 \times 10^6 \mu^+/s$
- Emittance
  H: $195.2\ \mathrm{mm} \cdot \mathrm{mrad}$
  V: $183.2\ \mathrm{mm} \cdot \mathrm{mrad}$
- $P \approx 93\%$

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

## $\mu$E1 @ 125 MeV/c

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

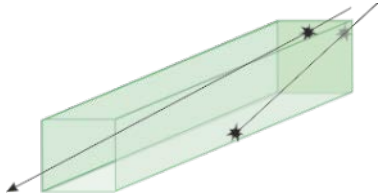
Final data taking at 3T



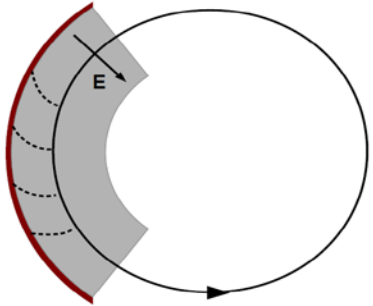
# Muon tagging and positron tracking

## Entrance trigger/tagger

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

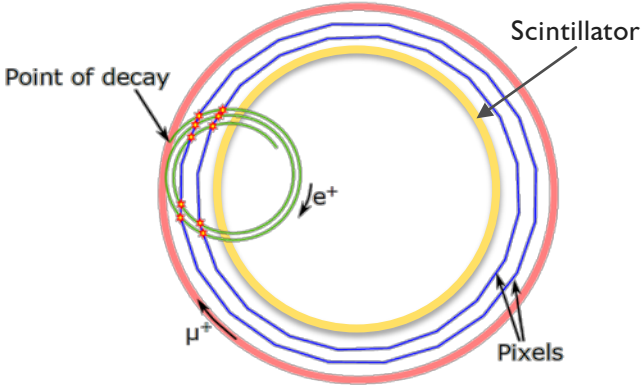


- Tagger
  - Muon track information for reconstruction of decay vertex

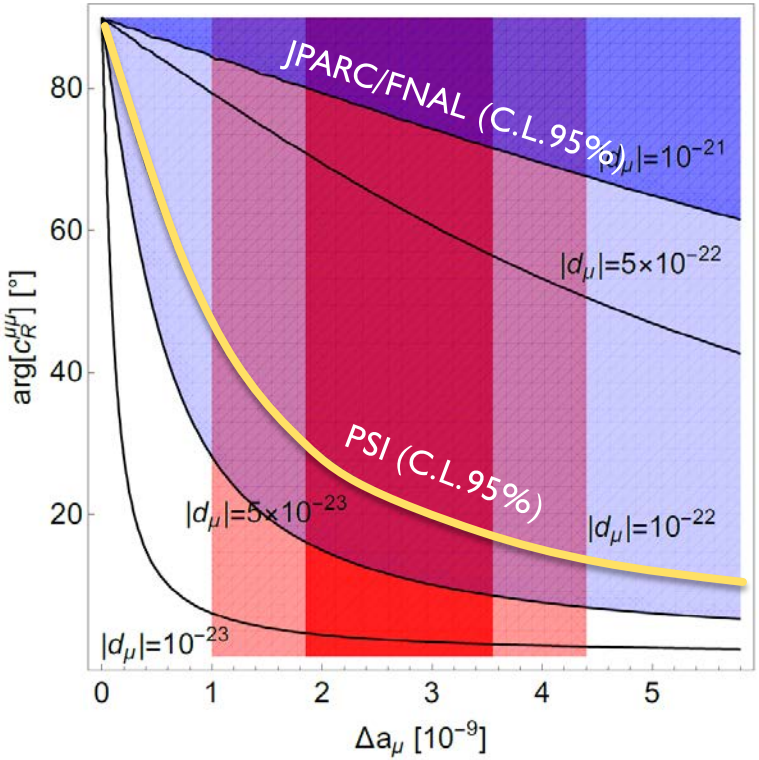



## Positron tracker

- 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 ($p_\mu = 125\mathrm{MeV}/c$) | $\gamma$ | 1.77 |
| Initial polarization | $P$ | 0.93 |
| Electric field ($B = 3T$) | $E_\mathrm{f}$ | $2\mathrm{MV/m}$ |
| Detection rate | | $60\mathrm{kHz}$ |
| Mean decay asymmetry | $\alpha$ | 0.3 |
| Detections (200days) | $N$ | $10^{12}$ |
| $\sigma = \hbar\gamma a_\mu/(2PE_\mathrm{f}\sqrt{N}\tau_\mu\alpha)$ | $<$ | $6\times10^{-23}$ ecm |

**Leptoquarks:** A. Djouadi ZPhysC(1989), E.C. Leskow PRD95(2017), A. Crivellin arXiv:2010.06593, I. Doršner 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 ( $\sim 4\mathrm{ns}$)

Farley *et al.*, PRL93(2004)

# Tentative schedule subject to funding

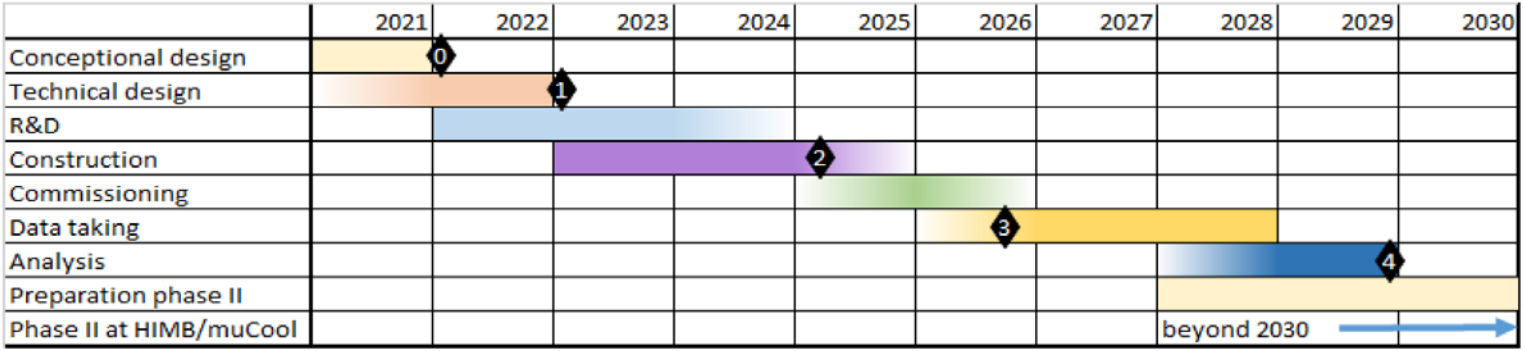



FIG. 25: Tentative schedule for the search of a muon EDM at PSI. Milestones are indicated as black diamonds. M0: Submission of experimental proposal to BVR committee. M1: Submission of technical design report to BVR, M2: delivery of magnet, M3: Start of data taking, M4: Final report of phase I and proposal for measurement at HIMB/muCool.

# 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

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

  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