Proposal to measure the muon electric dipole moment with a compact storage ring at PSI

Klaus Kirch

in collaboration with

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Louvain-La-Neuve, Nov 2007

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- Lepton dipole moments
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- A possible layout for PSI
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- Status of the project

Lepton dipole moments

Hamiltonian: $$\boldsymbol{\mathcal{H}} = -\vec{\boldsymbol{\mu}} \cdot \vec{\boldsymbol{B}} - \vec{\boldsymbol{d}} \cdot \vec{\boldsymbol{E}} \qquad \vec{\mu}, \vec{d} \,||\, \vec{\sigma}$$

Define *g* and η as dimension-less quantities describing magnetic and electric dipole moments, respectively:

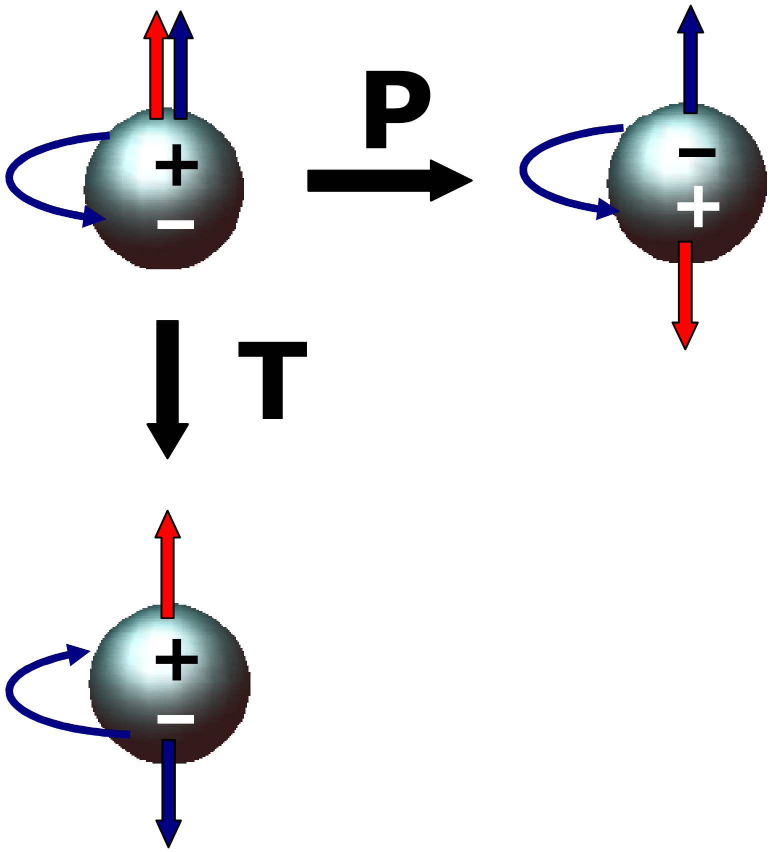
$$\mu = \frac{g}{2} \frac{e\hbar}{2m} \qquad d = \frac{\eta}{2} \frac{e\hbar}{2mc}$$

For a Dirac particle (i.e. lepton):
g = 2 (+ corrections) and
η = 0 (+ super-tiny corrections from CP-violating interactions)

* convenient to define: $$\mu = (1 + a) \frac{e\hbar}{2m} \qquad a = \frac{g-2}{2}$$

Lepton EDMs

M. Pospelov, A. Ritz: *Electric dipole moments as probes of new physics*, Annals of Physics 318 (2005) 119



$$\vec{\mu}, \vec{d} \,||\, \vec{\sigma}$$

- ***EDMs** in elementary particles (also nuclei, atoms and some molecules) **violate P and T** symmetries, therefore **violate CP** if CPT is conserved.*
  - ***No contributions from QED and strong interactions, only higher-order electroweak!***
- ***Current efforts are mainly focused on neutral particles (neutron, atoms).***
- ***But lepton EDMs are theoretically much cleaner.***

Standard model lepton EDMs

Fourth order electroweak,

F. Hoogeveen:
The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322

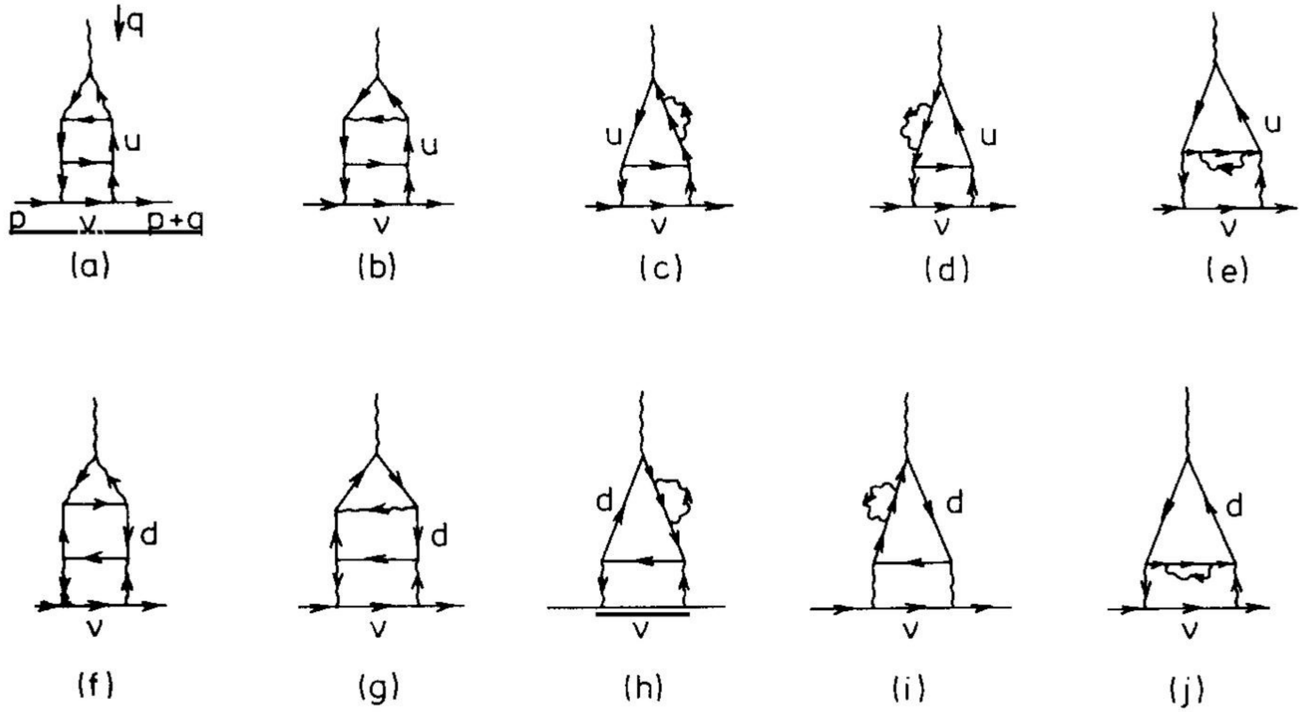


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

… + new physics?

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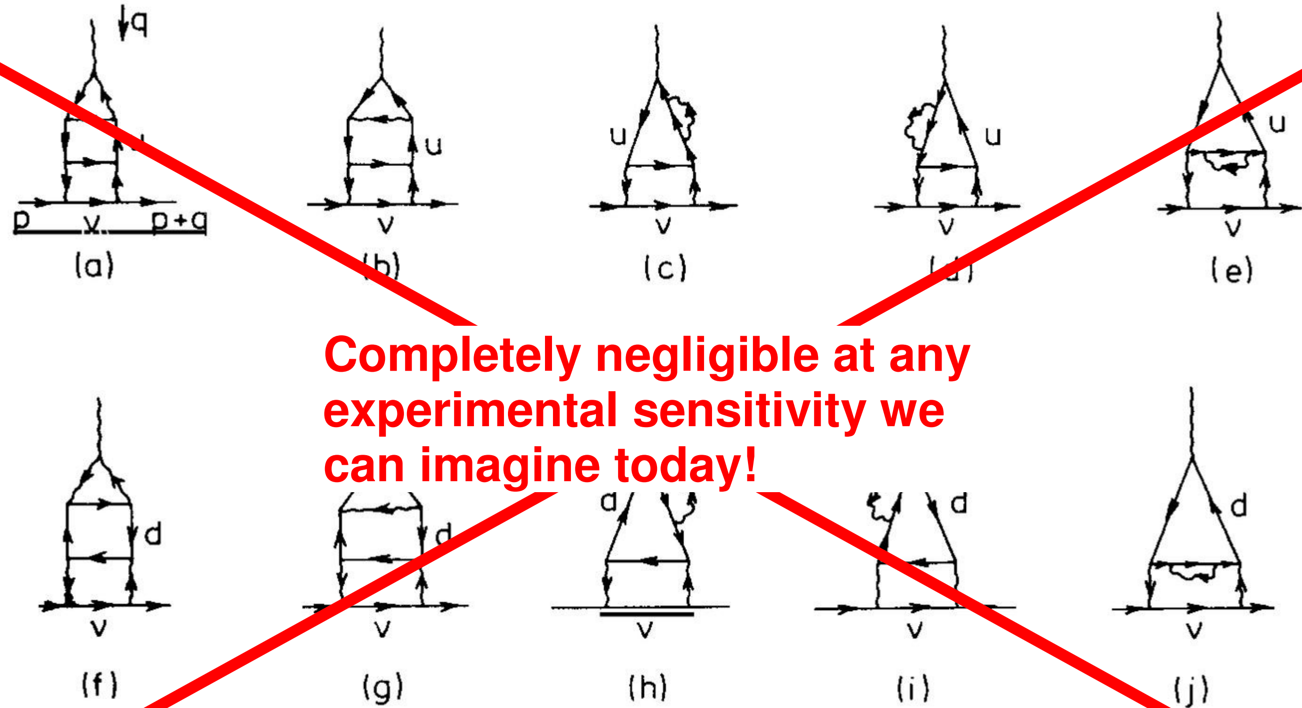


Completely negligible at any experimental sensitivity we can imagine today!

Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

… + new physics?

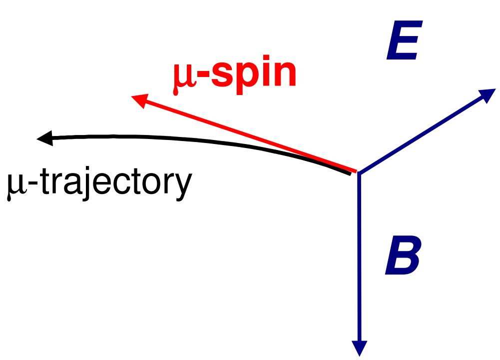
Much greater sensitivity to new, CP-violating physics!

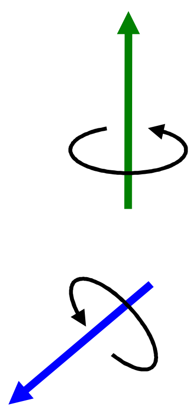
Muon spin precession in *B* and *E* field

Muon spin precession in the presence of *B* and *E* field,
perpendicular to each other and to the muon momentum:

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

Example:
B-field pointing down,
E-field radially outward:





$\vec{\omega}_a$: spin precession in orbital plane
("*g*–2" precession)

$\vec{\omega}_e$: spin precession out of orbital plane

$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e$ tilts the precession plane out of the orbital plane

Muon spin precession in *B* and *E* field

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

Strategy for (recent) *g*–2 measurement at storage rings:

- run at **"magic γ"**, $\gamma = 29.3$ ($p_\mu = 3.1$ GeV)

  $\Rightarrow$ no effect from electric fields, can use **electric focusing**
  (need for uniform *B* field precludes magnetic focusing)

- assume η small for measurement of a

  $\Rightarrow$ direct access to a if *B* is known

$$\vec{\omega} = -\frac{e}{m}a\vec{B}$$

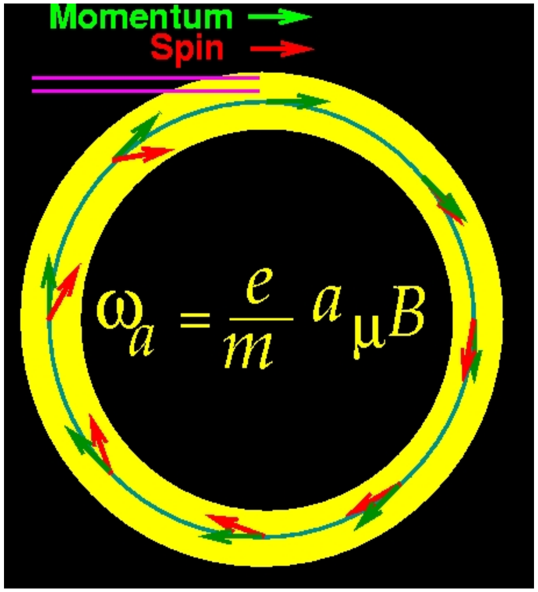
- look for small vertical oscillation to put a limit on η.
  - All recent limits have been obtained in this way (CERN, Brookhaven)
  - Plagued by systematics: *g*–2 precession interferes strongly!

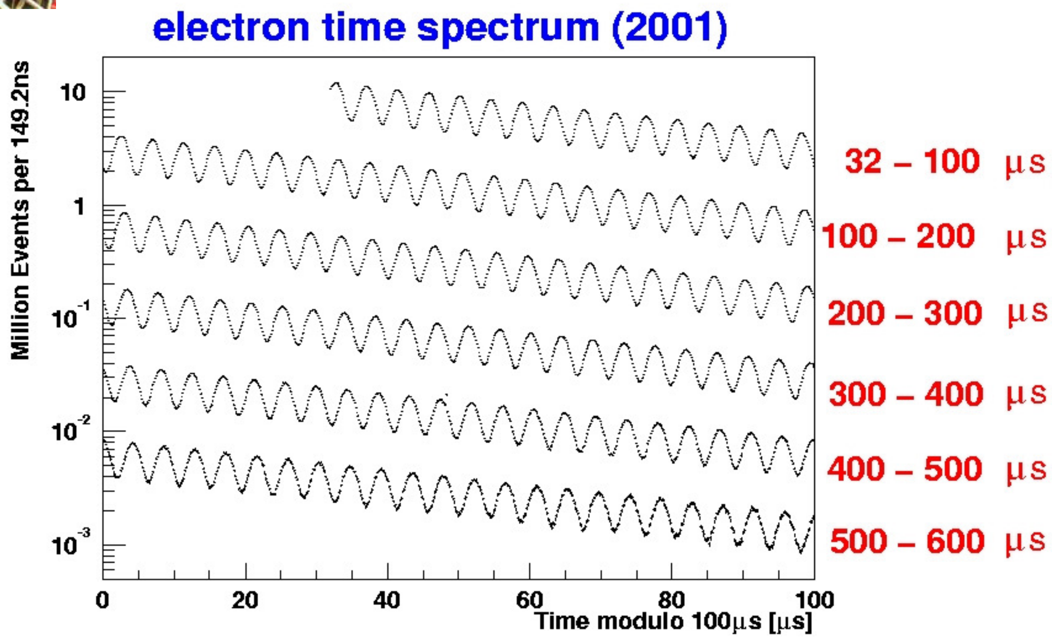
g–2 Measurement (E821@Brookhaven)

A 20-year effort to improve the precision on a_μ from 7 ppm to 0.5 ppm:

$$a_\mu = 0.001\,165\,920\,80\,(63)$$

G.W. Bennett et al.:
Final report of the E821 muon anomalous magnetic moment measurement at BNL,
Phys. Rev. D 73 (2006) 072003





g–2: the most recent state of affairs

$$a_\mu(\text{exp}) = 0.001\ 165\ 920\ 80\ (63)$$

(0.54 ppm)

G.W. Bennett et al.:
Final report of the E821 muon anomalous magnetic moment measurement at BNL,
Phys. Rev. D 73 (2006) 072003

$$a_\mu(\text{SM}) = 0.001\ 165\ 918\ 04\ (51)$$

(0.44 ppm)

K. Hagiwara, A.D. Martin, D. Nomura, T. Teubner:
Improved predictions for g-2 of the muon and $\alpha_{QED}(M_Z^2)$,
hep-ph/0611102

$$a_\mu(\text{exp}) - a_\mu(\text{SM}) = (27.6 \pm 8.1) \times 10^{-10}$$

3.4σ discrepancy!

- New physics or not?
- The deviation is consistent with LHC-accessible SUSY in the few 100 GeV range...
- A follow-up of E821 could potentially reduce the experimental error by a factor 2-5.
- Both, experiment and theory are not far from their limits.

For the (beautiful!) history of g–2, see:

F.J.M. Farley, Y.K. Semertzidis:
The 47 years of muon g–2,
Prog. Part. Nucl. Phys. 52 (2004) 1

J.P. Miller, E. de Rafael, B.L. Roberts:
Muon (g–2): Experiment and Theory ,
arXiv:hep-ph/0703049

E969:

B.L. Roberts:
Muon (g–2): Past, present and future,
Nucl. Phys. Proc. Suppl. 155 (2006) 372

μEDM at g–2 storage rings

- Search for a **vertical oscillation signal** in *g*–2 data (vertical segmentation of some of the electron detectors)

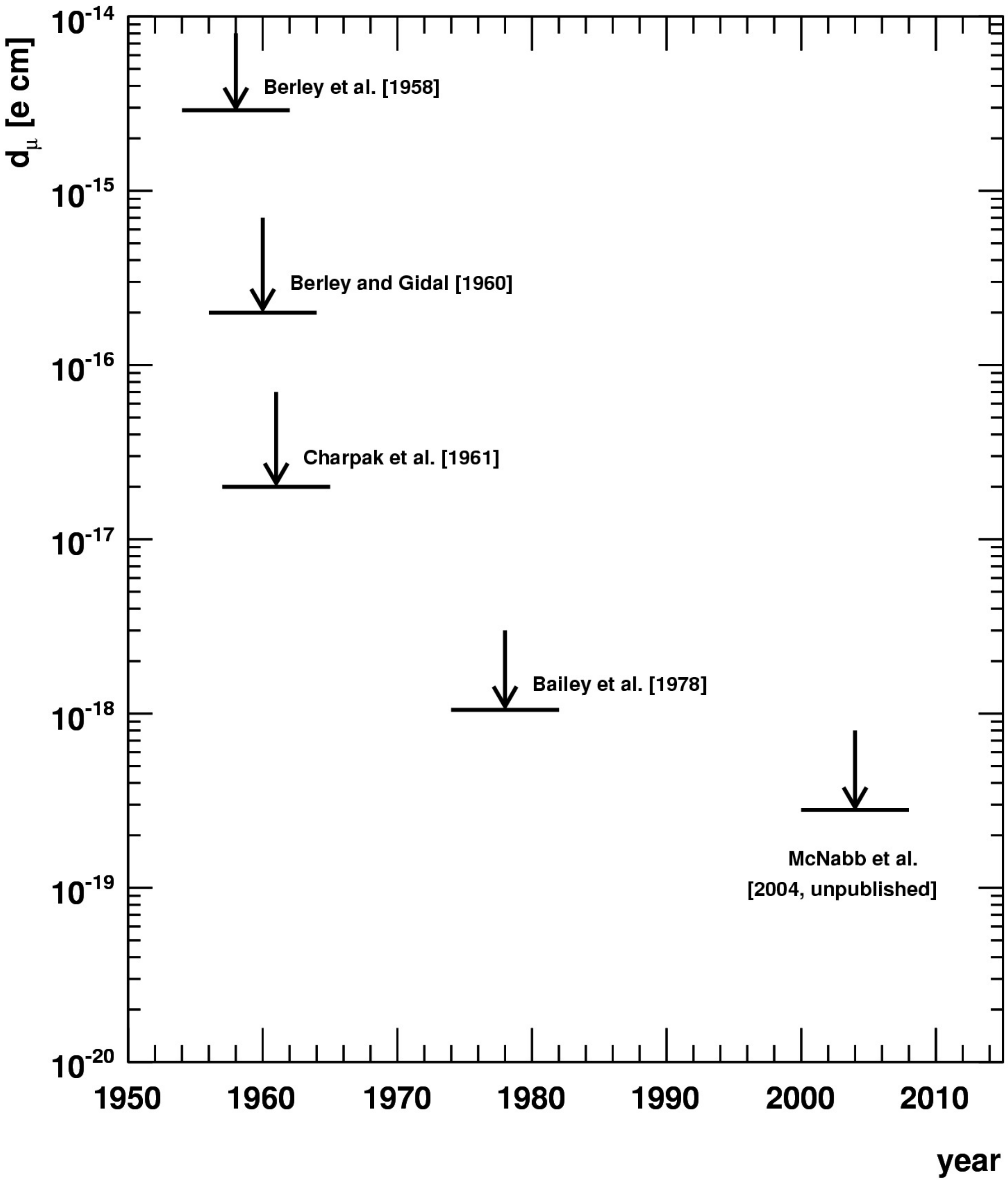
- Seriously limited by two effects:

  1) ***g–2* rotation** of spin strongly suppresses the effect of ω_e

  2) **Trajectories** of the decay electrons are **very different** at the two extremes of vertical oscillation, leading to large systematic effects.

- Best current limit from **Brookhaven E821**: $d_\mu < 2.4 \times 10^{-19}\, e\,\mathrm{cm}$
  - Only preliminary, but soon to be published (L. Roberts).
  - Only **modest improvement** with respect to previous (CERN) experiment.

R. McNabb et al.:
hep-ex/0407008, unpublished



History of *μEDM* measurements

D. Berley et al.,
Phys. Rev. Lett. 1 (1960) 144

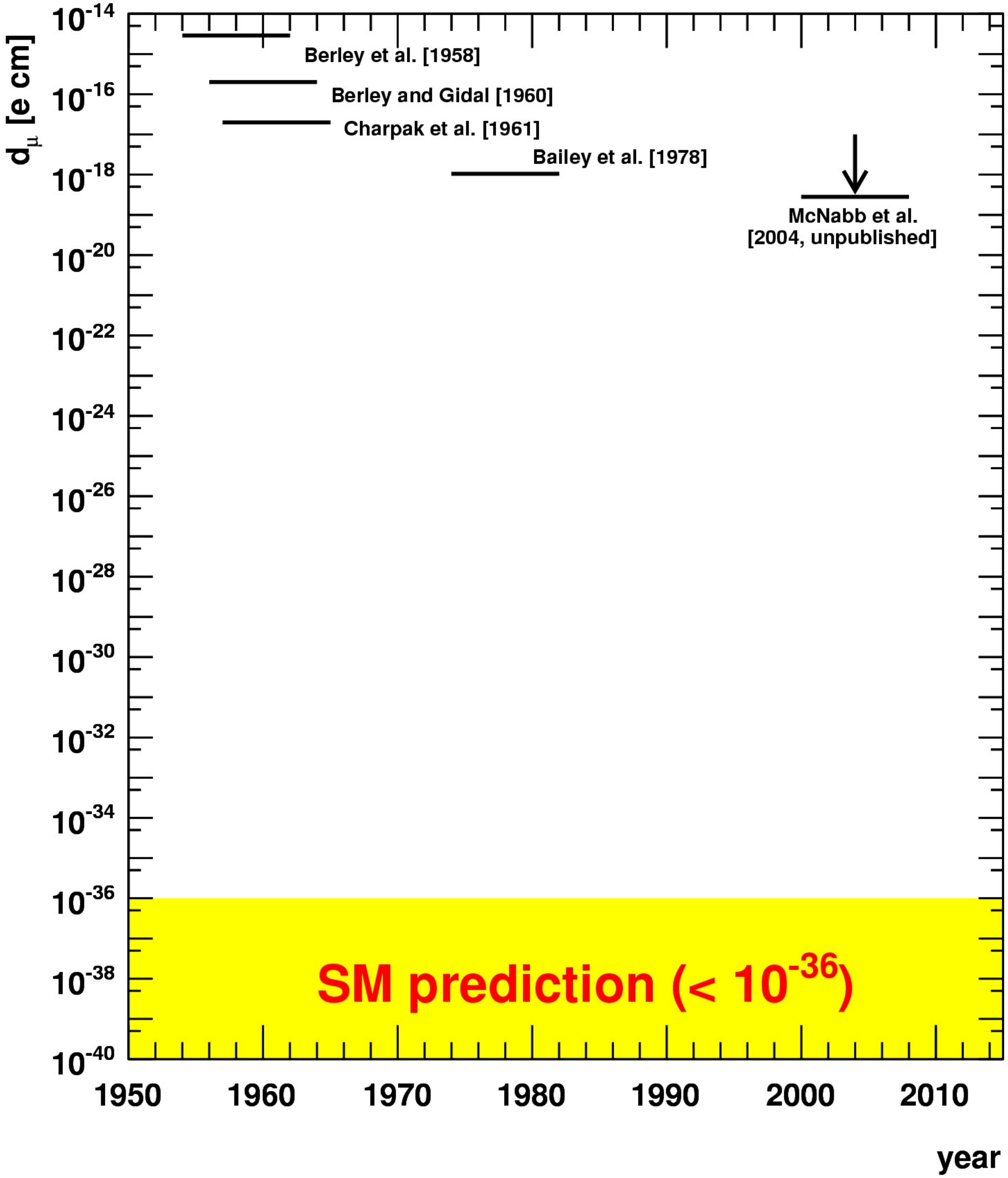
D. Berley, G. Gidal,
Phys. Rev. 118 (1960) 1086

G. Charpak et al.,
Nuovo Cim. 22 (1961) 1043

J. Bailey et al.,
J. Phys. G: Nucl. Phys. 4 (1978) 345

R. McNabb et al.,
hep-ex/0407008, unpublished

Stalling progress with conventional storage ring method...
... need new method,
but first look at motivations



What is the motivation to go below 10^{-19} *e* cm?

Various:

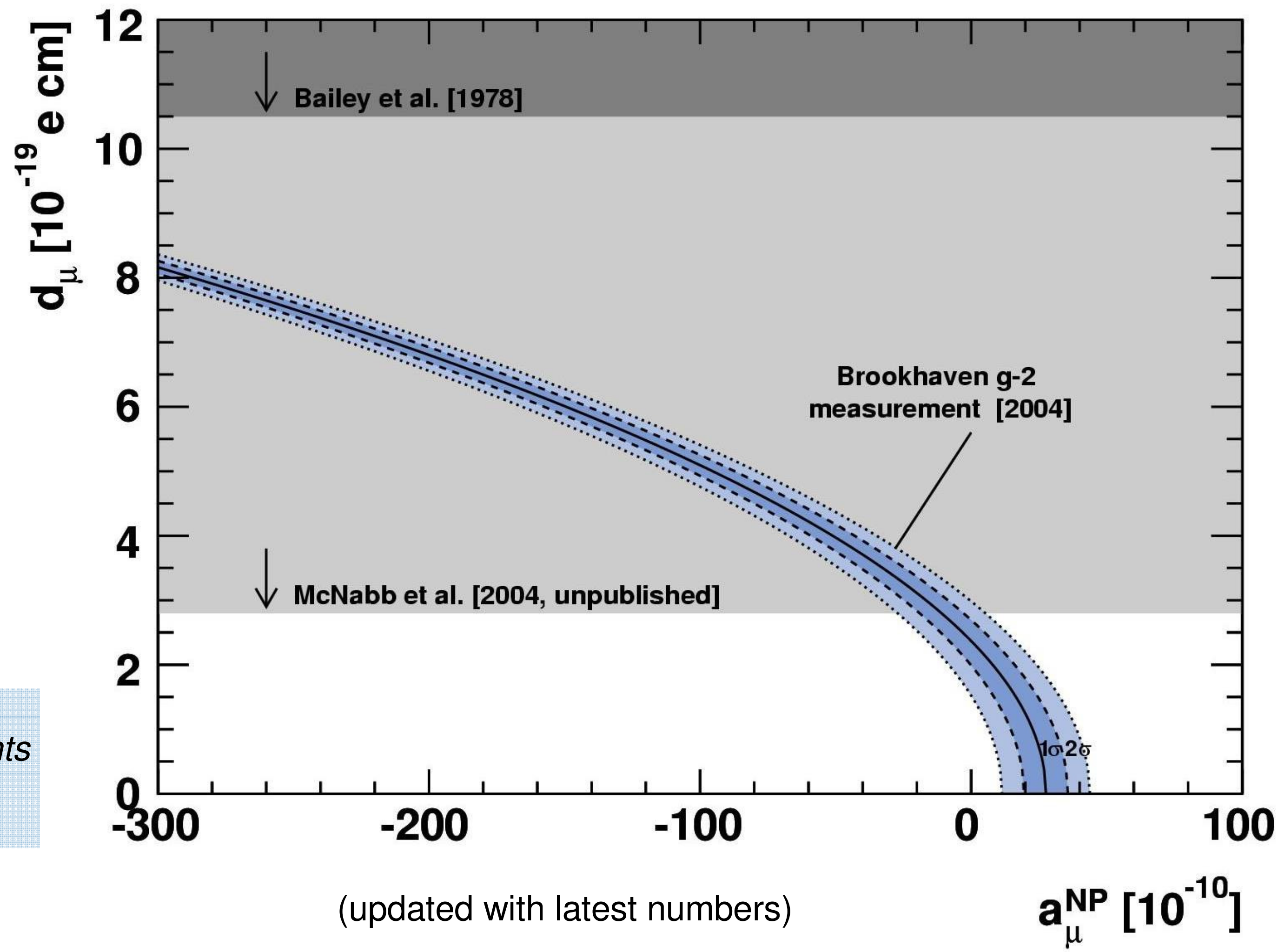
- model independent …
- model dependent …
- forget models …

The *g*–2 anomaly isn't?

J. Feng, T.M. Matchev, Y. Shadmi:
The Measurement of the Muon's Anomalous Magnetic Moment Isn't,
Phys. Lett. B 555 (2003) 89

$$\omega_{\rm obs} = \sqrt{\omega_a^2 + \omega_e^2}\ !$$

See already: **J. Bailey et al.:**
New limits on the electric dipole moments of positive and negative muons,
J. Phys. G: Nucl. Phys. 4 (1978) 345



(updated with latest numbers)

Generic new-physics dipole moment

If one assumes that both non-SM MDM (a_μ^{NP}) and EDM (d_μ) are manifestations of the same **new-physics object:**

$$a_\mu^{\mathrm{NP}} \frac{e}{2m_\mu} = \mathrm{Re}D \quad \text{and} \quad d_\mu^{\mathrm{NP}} = \mathrm{Im}D$$

with *D* a **general dipole operator** (W. Marciano),

$$D = |D| \exp(i\phi_{\mathrm{CP}})$$

then the Brookhaven measurement can be interpreted as

$$d_\mu^{\mathrm{NP}} = 2.7 \times 10^{-22} e\,\mathrm{cm} \frac{a_\mu^{\mathrm{NP}}}{27.6 \times 10^{-10}} \tan\phi_{\mathrm{CP}}$$

i.e. either d_μ is **of order 10^{-22} *e* cm**,
or the CP phase is strongly suppressed!

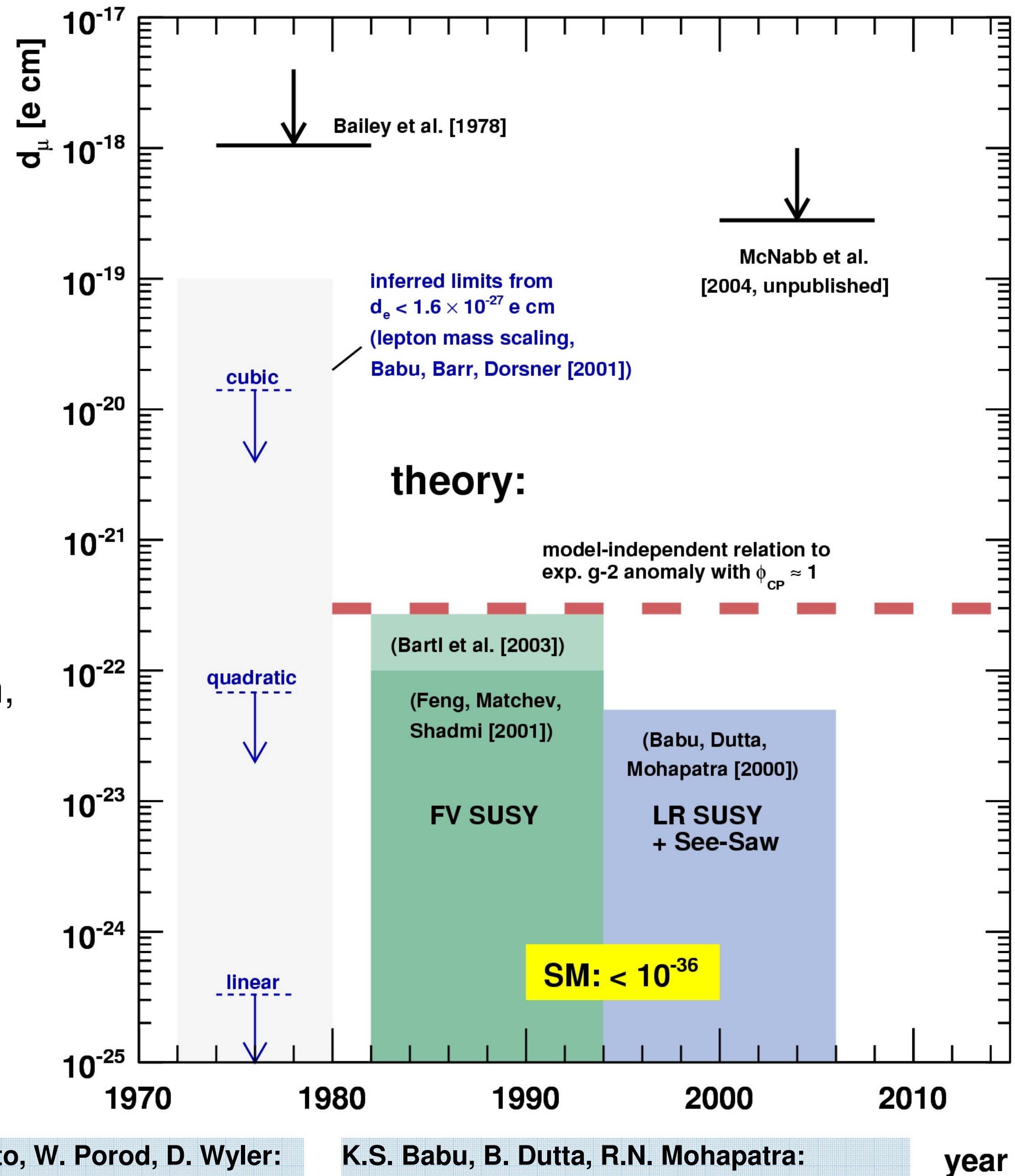
J.L. Feng, K.T. Matchev, Y. Shadmi:
Theoretical Expectations for the Muon's Electric Dipole Moment,
Nucl. Phys. B 613 (2001) 366

Model-specific predictions

- Most models predict lepton EDMs to scale **linearly with mass**.
  - Strong bound on d_μ from $d_e < 1.6 \times 10^{-27}$ *e* cm!
- Some models, however, predict quadratic and cubic mass scaling

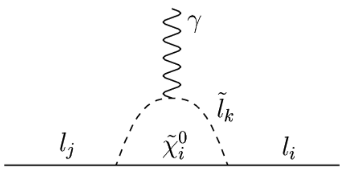
K.S. Babu, S.M. Barr, I. Dorsner:
Scaling of lepton dipole moments with lepton mass,
Phys. Rev. D 64 (2001) 053009

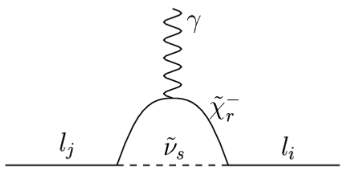
- Some SUSY variants can give up to 10^{-22} *e* cm, but this involves a lot of tuning
  - Flavour-violating SUSY a good candidate, but predictions **need to be updated** in view of new experimental limits on $\tau \rightarrow \mu\gamma$!
  - Bartl et al. give $d_\mu \simeq 2.7 \times 10^{-22}$ *e* cm for $\varphi_\mu = \pi/2$ (SUSY-parameter μ) from stau-smuon mixing, based on BF($\tau \rightarrow \mu\gamma$) < 1.1×10^{-6}.
  - The latest limit from Belle reads BF($\tau \rightarrow \mu\gamma$) < 4.5×10^{-8} ...



A. Bartl, W. Majerotto, W. Porod, D. Wyler:
Effect of supersymmetric phases on lepton dipole moments and rare lepton decays,
Phys. Rev. D 68 (2003) 053005

K.S. Babu, B. Dutta, R.N. Mohapatra:
Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing,
Phys. Rev. Lett. 85 (2000) 5064





MSSM with LR, flavor mixing and complex phase

A. Bartl, W. Majerotto, W. Porod, D. Wyler:
Effect of supersymmetric phases on lepton dipole moments and rare lepton decays,
Phys. Rev. D 68 (2003) 053005

- Input: MSSM at point SPS1a
- Add flavor-violating terms that saturate experimental limits (as of 2003!) on d_e, d_μ, d_τ, a_e, a_μ, a_τ, *BF*($\mu \rightarrow e\gamma$), *BF*($\tau \rightarrow \mu\gamma$), *BF*($\tau \rightarrow e\gamma$)
- *Smuon-stau mixing can give large d_μ:*

C. $\tilde{\mu}$-$\tilde{\tau}$ mixing

In this section we consider mixing between the second and the third generation by adding the following flavor violating terms to our reference point: $M^2_{L,23} = 1500\ \mathrm{GeV}^2$, $M^2_{E,23} = 2000\ \mathrm{GeV}^2$, $A_{32} = A_{23} = 20$ GeV, yielding BR($\tau \rightarrow \mu\gamma$) $= 1.0 \times 10^{-6}$. The effect of the phases is shown in Fig. 7. We see the branching ratio BR($\tau \rightarrow \mu\gamma$) can vary by a factor 2 when changing the phases from 0 to π.

If one takes $\varphi_\mu = \pi/2$ then one finds $d_\mu = (-2.7 \pm 0.1) \times 10^{-22}$ e cm varying only slightly with the flavor violating phases. Note that this value is clearly in the reach of future experiments [26]. In the case of BR($\tau \rightarrow \mu\gamma$) we find a range of 2.5×10^{-7}–8.5×10^{-7} and the functional dependence on the phases are shifted by $\pi/2$ for $\varphi_{M^2_{E,23}}$ and $-\pi/2$ in the remaining cases.

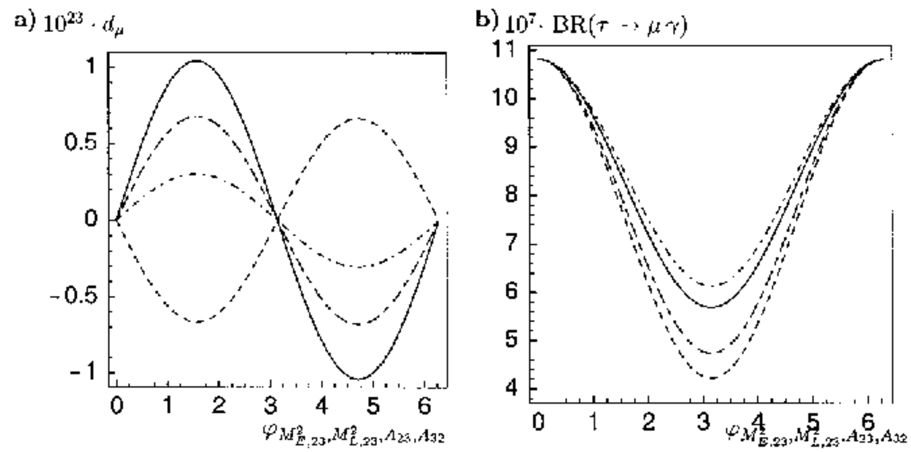


FIG. 7. (a) d_μ and (b) BR($\tau \rightarrow \mu\gamma$) as a function of $\varphi_{M^2_{E,23}}$ (full line), $\varphi_{M^2_{L,23}}$ (dashed line), $\varphi_{A_{23}}$ (dashed dotted line) and $\varphi_{A_{32}}$ (long-short dashed line) for $\varphi_\mu = 0$.

Bartl et al. use *BF*($\tau \rightarrow \mu\gamma$) < 1.1×10^{-6} (CLEO 2000)

Belle 2007: BF < 4.5×10^{-8}

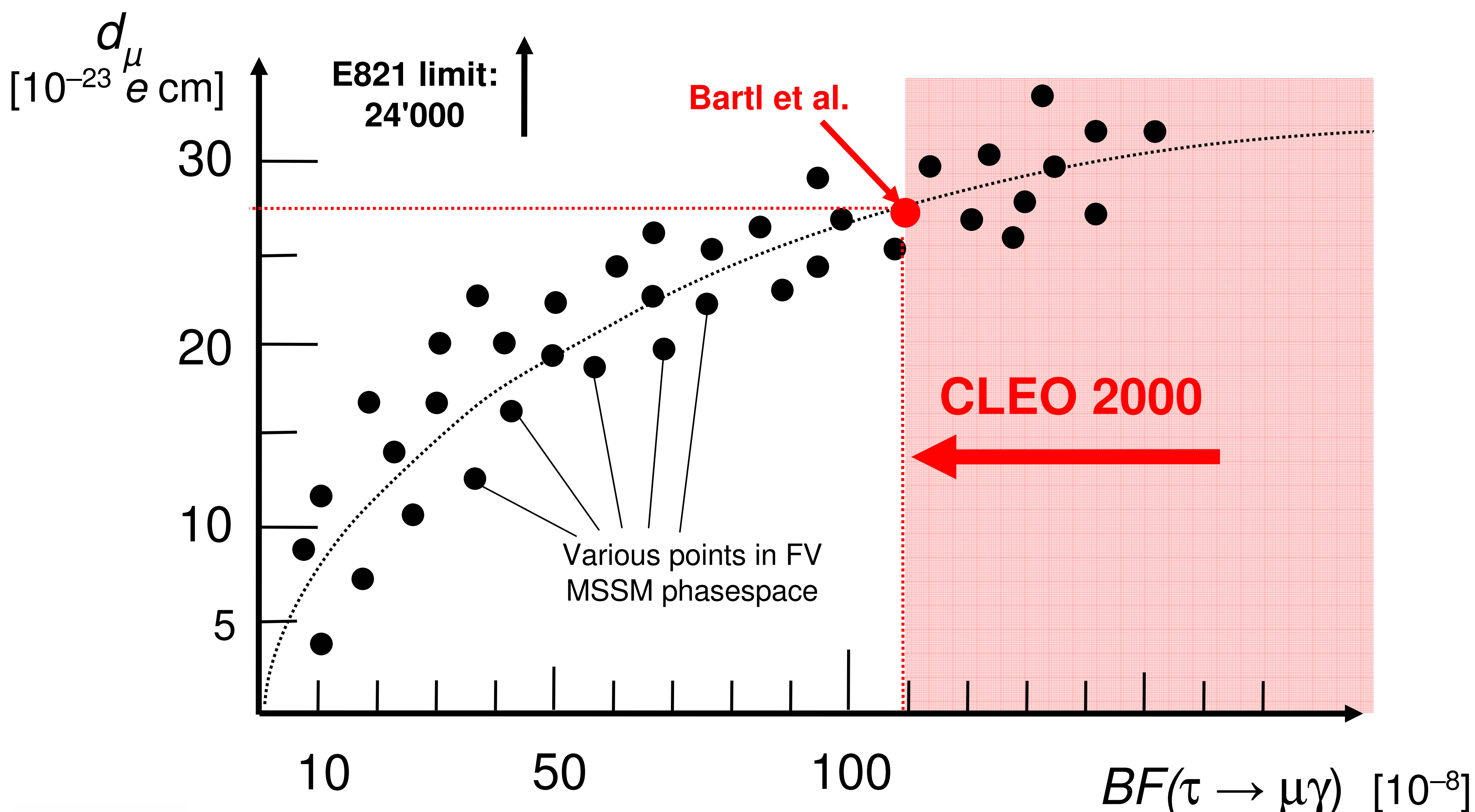
Belle Collab. (K. Hayasaka et al.)
New Search for $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ Decays at Belle,
hep-ex/0705.0650, submitted to Phys. Lett. B

BABAR 2007: BF < 6.8×10^{-8}

BABAR Collab. (B. Aubert et al.):
Search for lepton flavor violation in the decay $\tau \rightarrow \mu\gamma$,
Phys. Rev. Lett. 95 (2005) 041802

- Bartl et al. gave a snapshot of the situation in 2003.
- We need a systematic evaluation as a function of **BF($\tau \to \mu\gamma$)** in order to assess the situation now *and in future.*

G. Hiller (Dortmund) and collaborators from the Helsinki-Dortmund collaboration are working on it.



- New Belle limit has dramatic impact (on a linear scale)
- But ~ 5×10^{-23} *e* cm still possible in FV SUSY.
- We shall soon find out!

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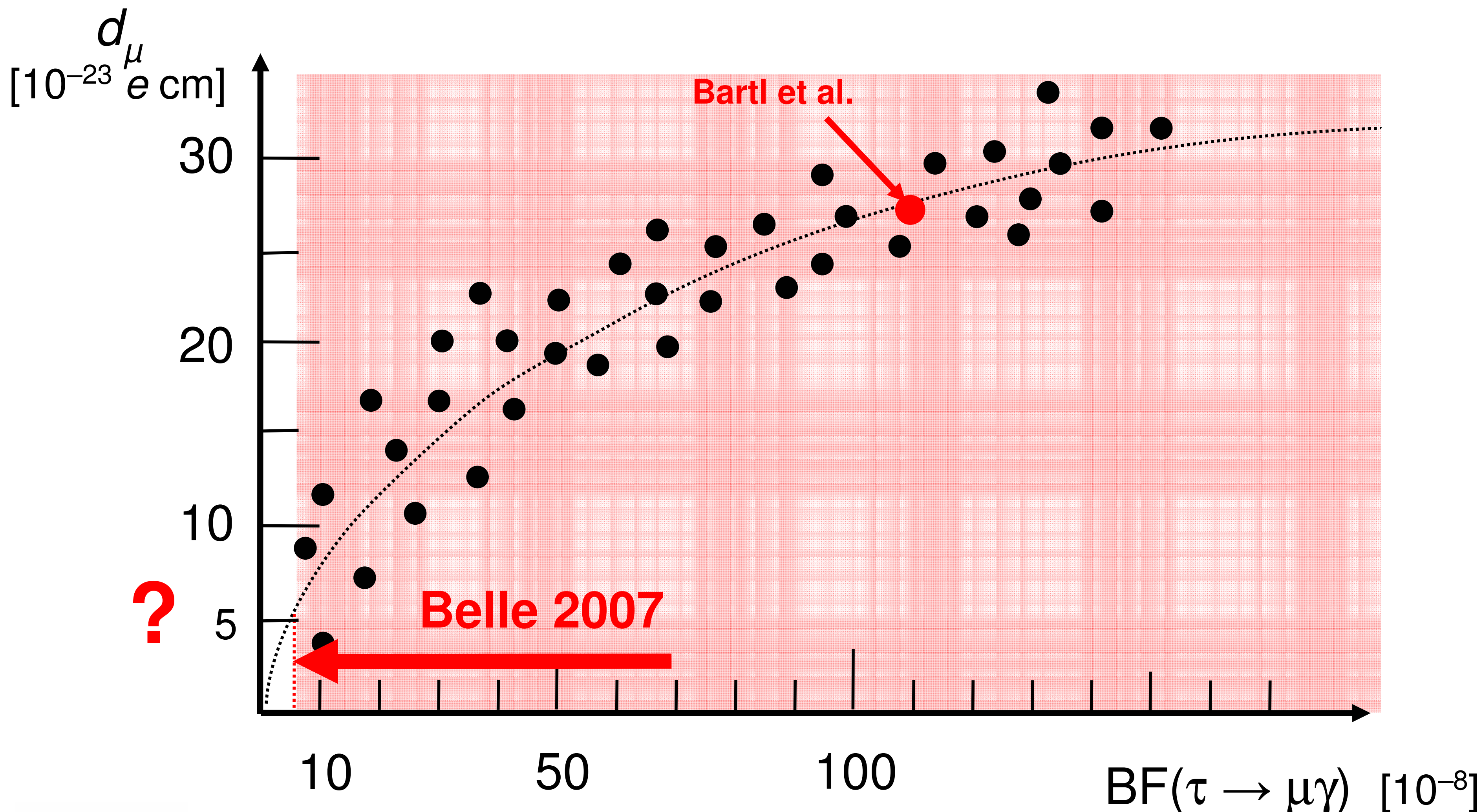

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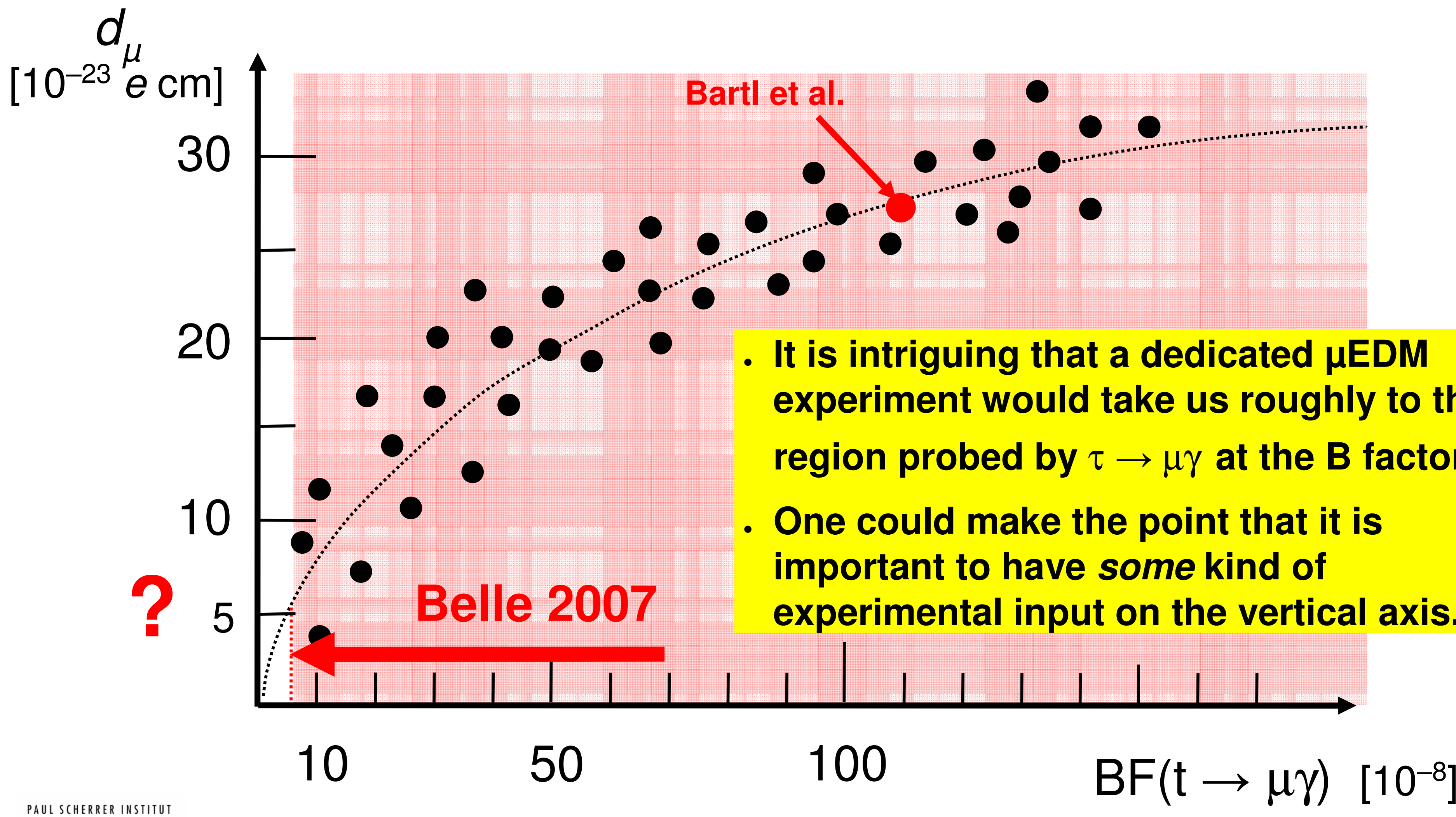


- **It is intriguing that a dedicated µEDM experiment would take us roughly to the region probed by $\tau \to \mu\gamma$ at the B factories!**
- **One could make the point that it is important to have *some* kind of experimental input on the vertical axis...**

Muon spin precession in *B* and *E* field

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

New method for EDM measurement: the "frozen spin" technique!

- Go to lower momentum, install a "**magic *E* field**" (radially), such that ω_a vanishes completely: $E \approx aBc\beta\gamma^2$
- The spin remains parallel to the momentum along the orbit ("frozen spin")
- In the presence of an EDM ($\eta \neq 0$) the spin is slowly rotated out of the orbital plane.
- **Much superior sensitivity** than with parasitic approach!

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

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
Phys. Rev. Lett. 93 (2004) 052001

J-PARC letter of intent

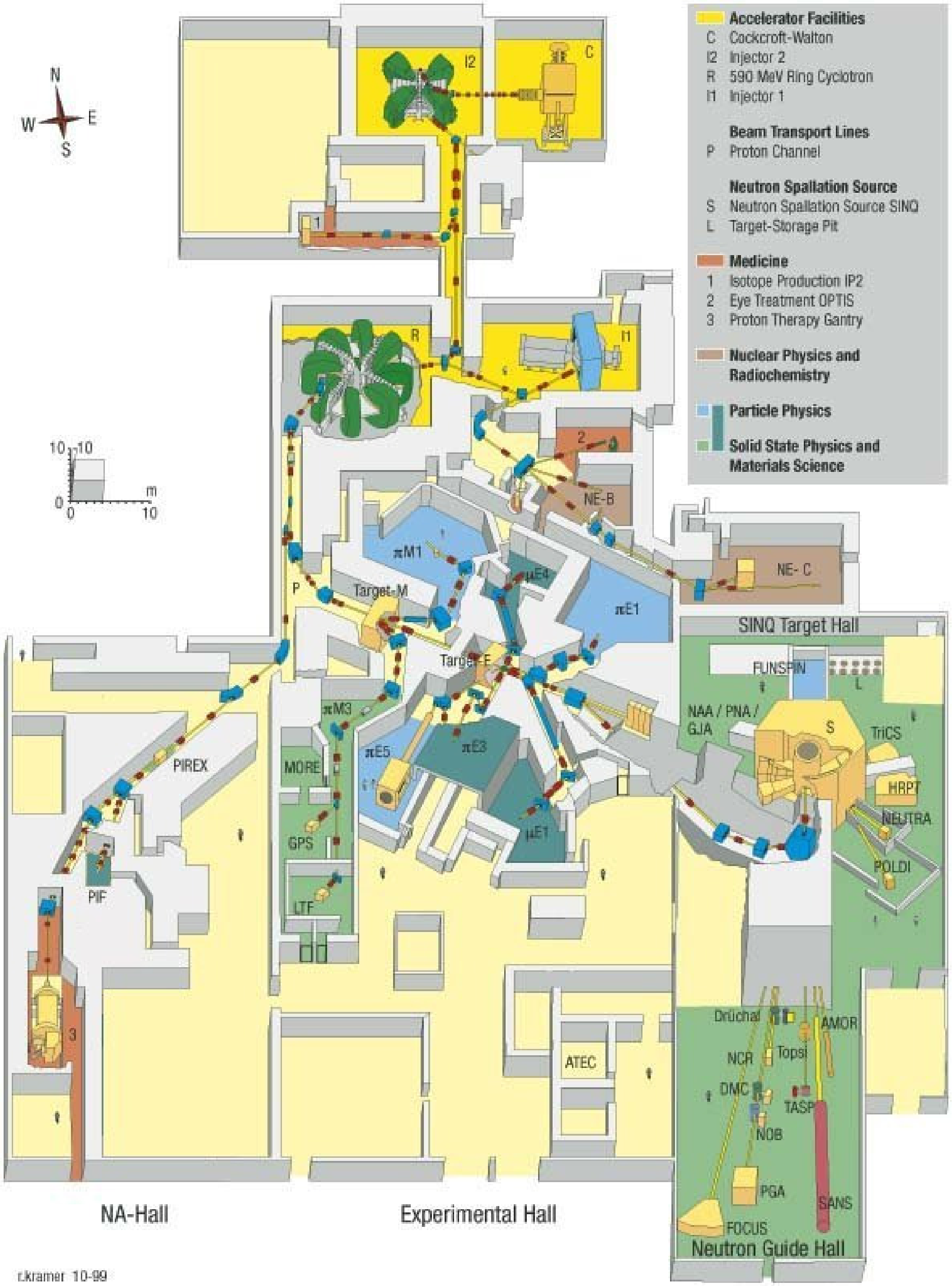
A. Silenko et al.:
J-PARC Letter of Intent: Search for the Permanent Muon Electric Dipole Moment at the 10^{-24} e cm Level.

- Semertzidis, Farley et al. in 2003 proposed an experiment exploiting the frozen spin technique at **J-PARC** (PRISM-II FFAG).
- Design: **7-m radius ring**, with $B = 0.25$ T, $E = 2$ MV/m and $p = 500$ MeV/c ($\gamma\tau = 11$ µs).
- Estimated sensitivity is around **10^{-24} *e* cm**
- So far a “virtual project”, realization not likely before 2015.

Can one do this at PSI with lower energy muons?

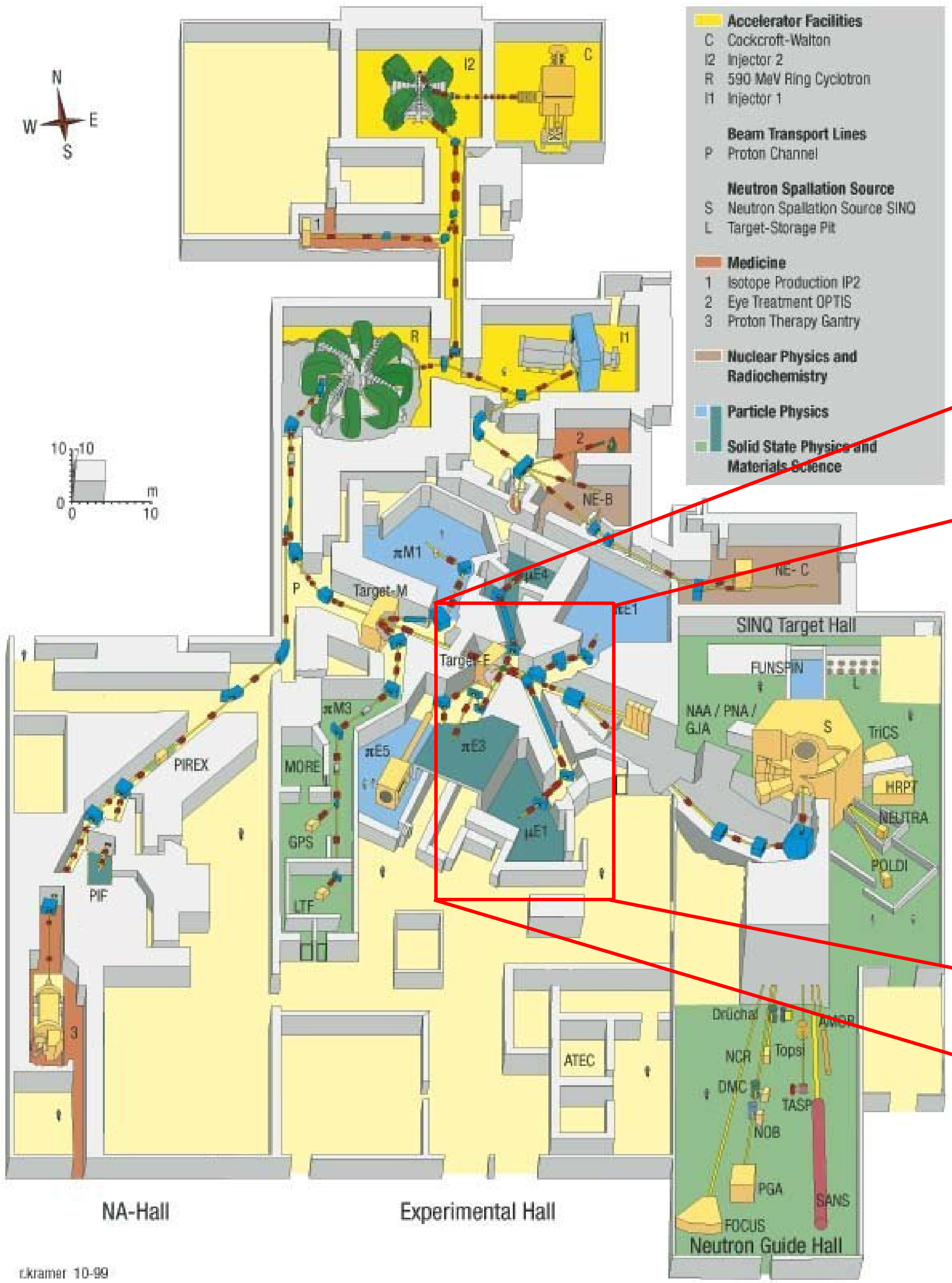

A µEDM experiment at PSI?

Muons at PSI

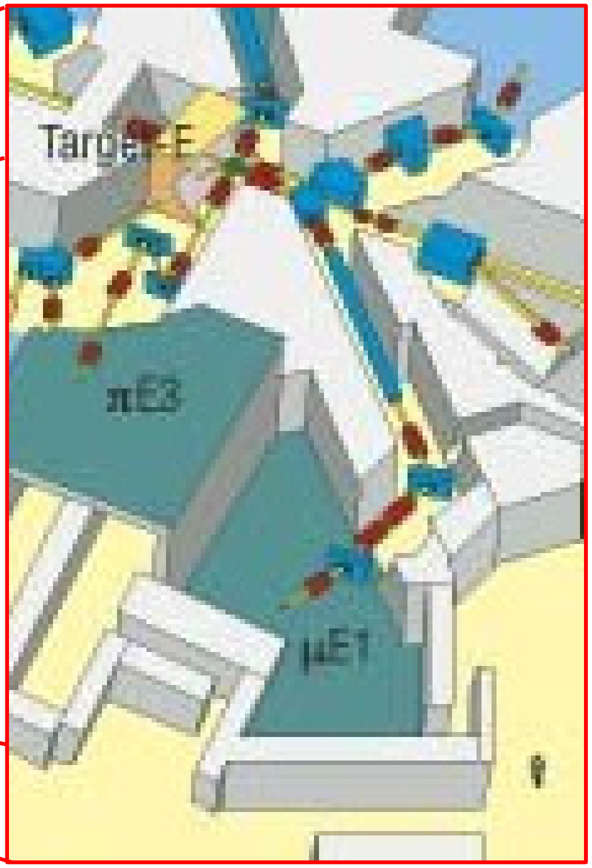


Accelerator Facilities
C Cockcroft-Walton
I2 Injector 2
R 590 MeV Ring Cyclotron
I1 Injector 1
Beam Transport Lines
P Proton Channel
Neutron Spallation Source
S Neutron Spallation Source SINQ
L Target-Storage Pit
Medicine
1 Isotope Production IP2
2 Eye Treatment OPTIS
3 Proton Therapy Gantry
Nuclear Physics and Radiochemistry
Particle Physics
Solid State Physics and Materials Science
N
W
E
S
NE-B
NE- C
πM1
μE4
Target-M
πE1
SINQ Target Hall
FUNSPIN
Target-E
πM3
NAA / PNA / GJA
TriCS
PIREX
MORE
πE5
πE3
HRPT
NEUTRA
GPS
μE1
POLDI
PIF
LTF
Drüchal
AMOR
NCR
Topsi
DMC
TASP
NOB
ATEC
PGA
SANS
FOCUS
NA-Hall
Experimental Hall
Neutron Guide Hall
r.kramer 10-99

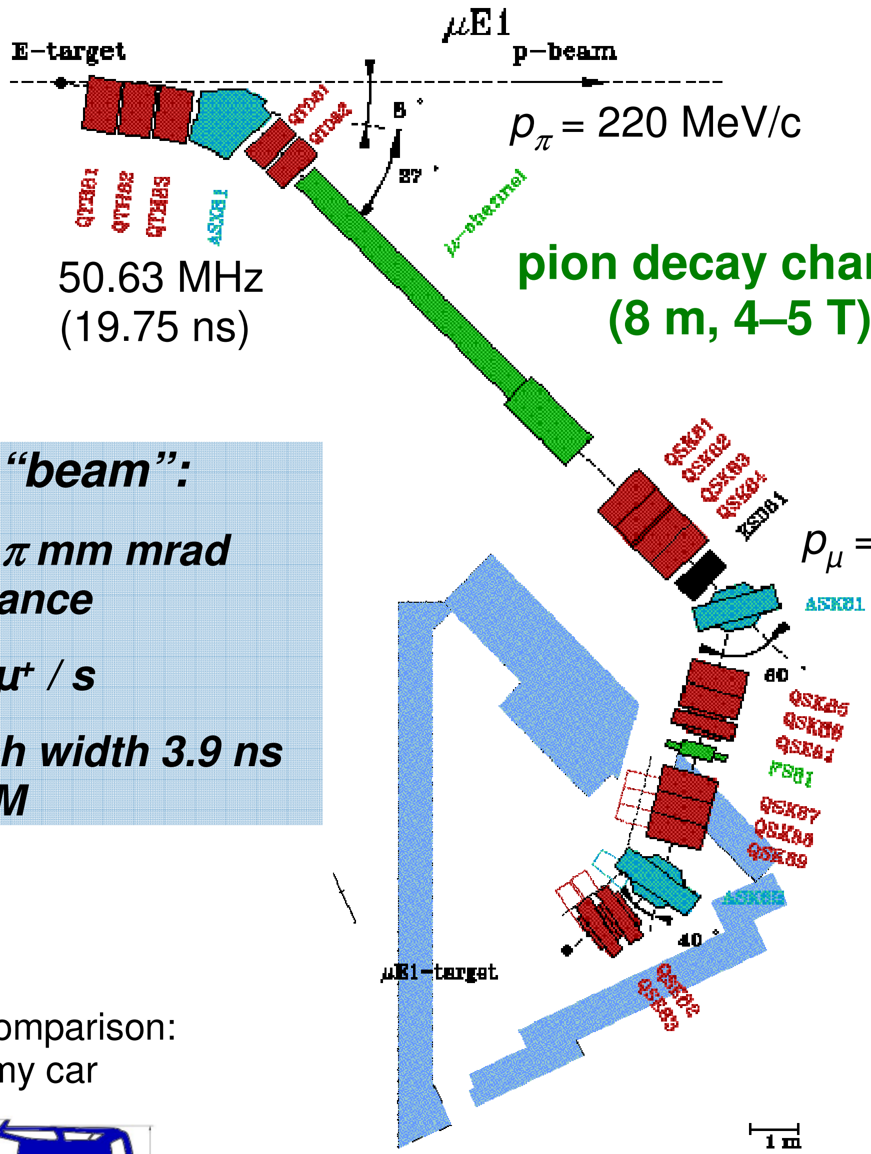
Muons at PSI



μE1 area



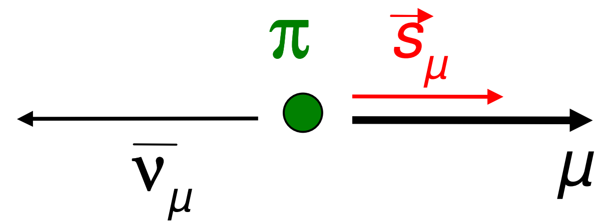
μE1 beamline and area



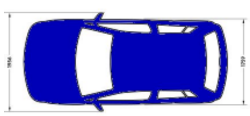
Existing infrastructure

Muon "beam":

- ***~400 π mm mrad emittance***
- ***~10^8 μ^+ / s***
- ***Bunch width 3.9 ns FWHM***



For comparison:
my car



I.C. Barnett et al. :
Nucl. Instr. and Meth. A 455 (2000) 329;
also: http://ltp.web.psi.ch

Concept for an experiment at PSI

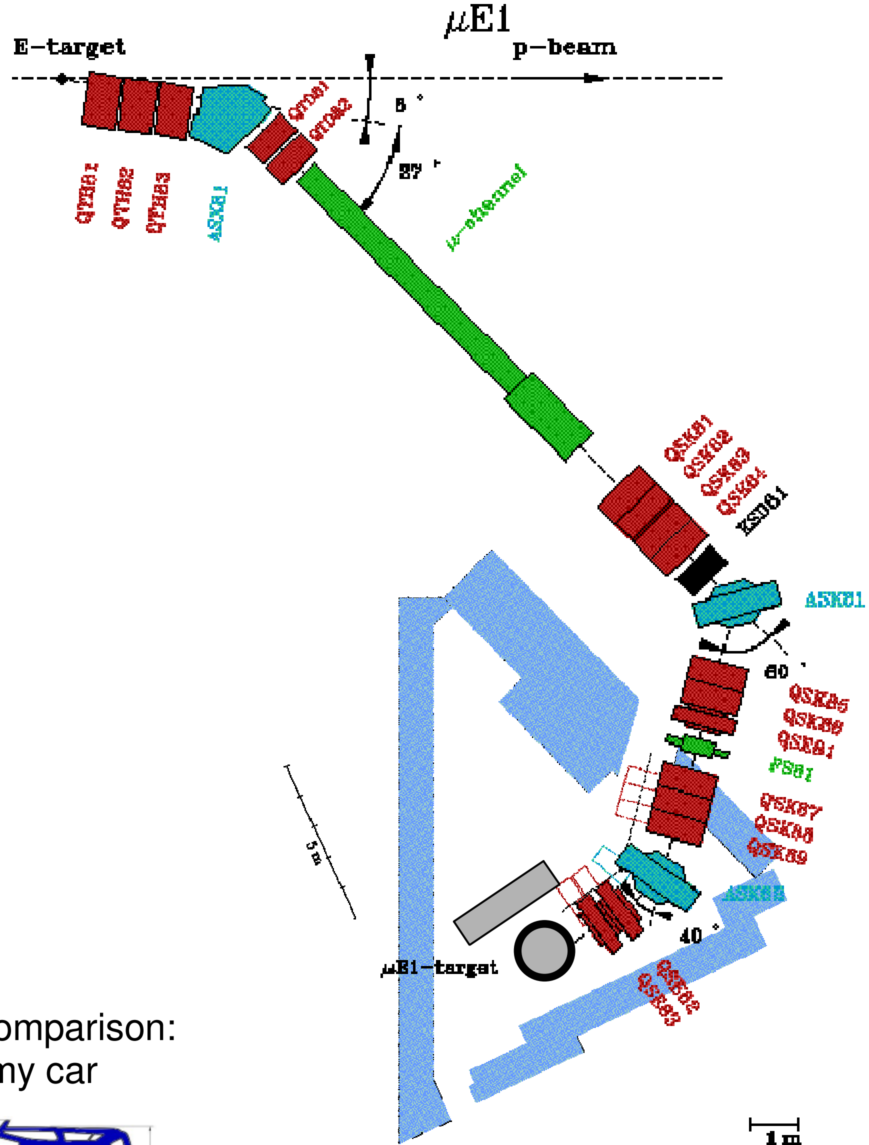
Apply frozen spin technique at **lower momentum** than JPARC:

- *PSI μE1:* p_μ=125 MeV/c (β = 0.76, γ= 1.55), P_μ = 92%
- Choose B = 1 T (conventional magnet, straightforward change of polarity)

→ **42 cm orbit radius**, radial E-field 0.64 MV/m (64kV/10cm gap).

Trade off high intensity of muon beam for **beam quality**, selecting the muons to be injected into the ring:

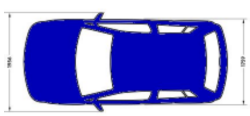
- Reduce from 100 MHz to ~200 kHz
- **One muon at a time!** Average measurement time $\approx \gamma\tau_\mu$ = 3.4 μs.
- Assume run-time of 2×10^7 s, times 200 kHz gives 4×10^{12} electron decays (per year)
- Clockwise and counter-clockwise operation (systematics)
- Positively and negatively charged muons can be injected (systematics)



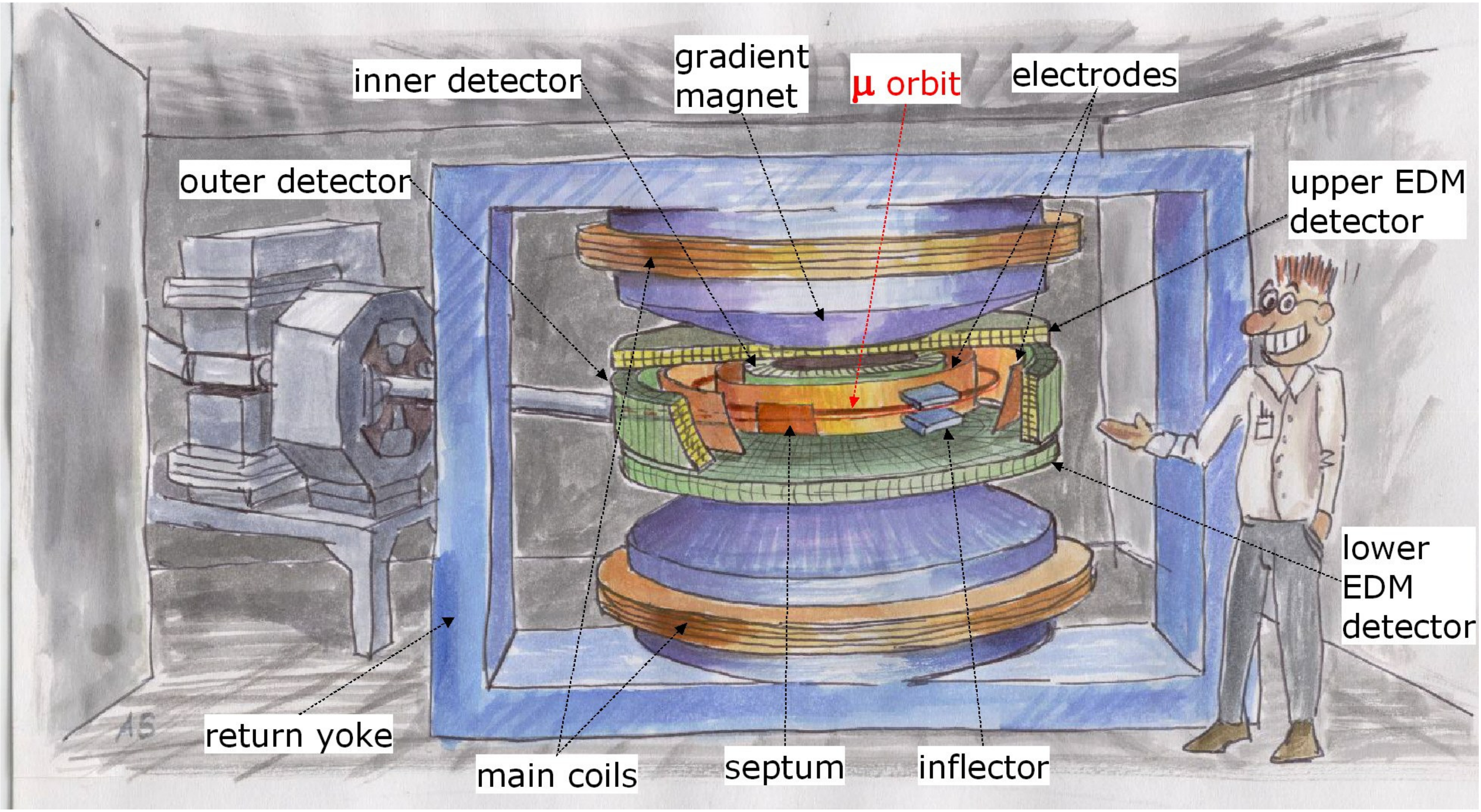
µE1 beamline and area

A ~1-m-diameter storage ring with support fits in comfortably

For comparison:
my car



Artist's impression (A. Streun)



Sensitivity estimate

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
Phys. Rev. Lett. 93 (2004) 052001

Uncertainty on η from a simple asymmetry counting experiment with N decays:

$$\sigma_\eta = \frac{\sqrt{2}}{\gamma\tau(e/m)\beta BAP\sqrt{N}}$$

$$d_\mu = \frac{\eta}{2}\frac{e\hbar}{2m_\mu c} \simeq \eta \times 4.7 \times 10^{-14} e\,\mathrm{cm}$$

A : electron asymmetry, assume $A = 0.3$
P : polarization of muons

J-PARC proposal: $\gamma\tau$ = 11 µs, β = 0.978, P = 50%, B = 0.25 T

$\rightarrow\ \sigma_\eta = 4 \times 10^{-3}/\sqrt{N}$; $N = 4 \times 10^{16} \Rightarrow \sigma_\eta = 2 \times 10^{-11}$

$d_\mu < 10^{-24}\ e\,\mathrm{cm}$

PSI proposal: $\gamma\tau$ = 3.4 µs, β = 0.76, P = 90%, B = 1.0 T

$\rightarrow\ \sigma_\eta = 2.4 \times 10^{-3}/\sqrt{N}$; $N = 4 \times 10^{12} \Rightarrow \sigma_\eta = 10^{-9}$

$$\sigma_\eta = \frac{\sqrt{2}ac\gamma}{\tau(e/m)EAP\sqrt{N}}$$

$d_\mu < 5 \times 10^{-23}\ e\,\mathrm{cm}$

PAUL SCHERRER INSTITUT

Muon statistics is the dominant factor!

Main challenges

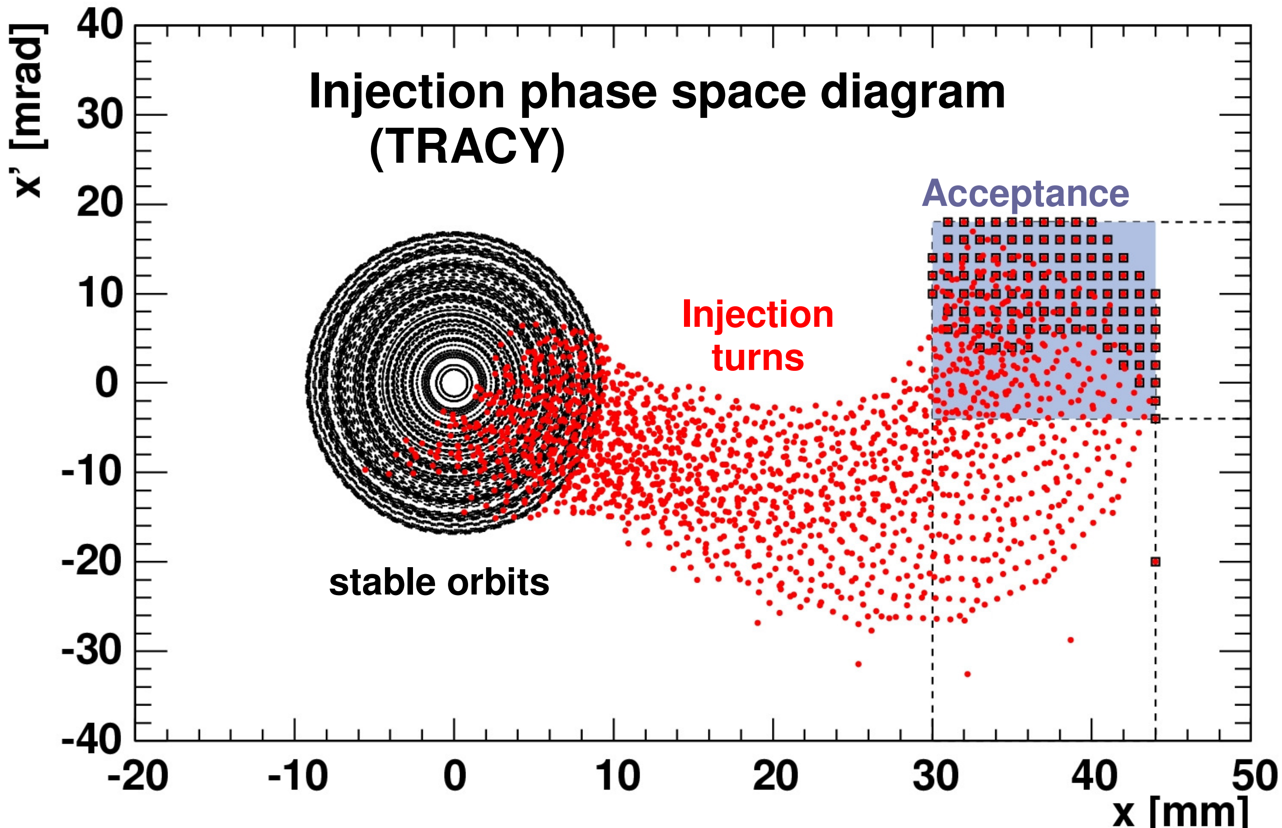
- **Injection**
  - Conventional kicker too slow, very short revolution time (11.6 ns)
  - Possible solution: **resonance injection** at half-integer tune using a non-linear field perturbator (inflector)
- **Injection trigger**
  - Minimal latency between detection of “good muon” and ramp-up of inflector
- ***E, B*-field setup, alignment and control**
- **Detector**
  - *E, B*-field, limited space, systematics issues
- **Data processing / storage**
  - $O(10^{12})$ muon decays, almost all of them carry interesting information

Injection study for μEDM project

- ***Andreas Adelmann, using TRACY program***

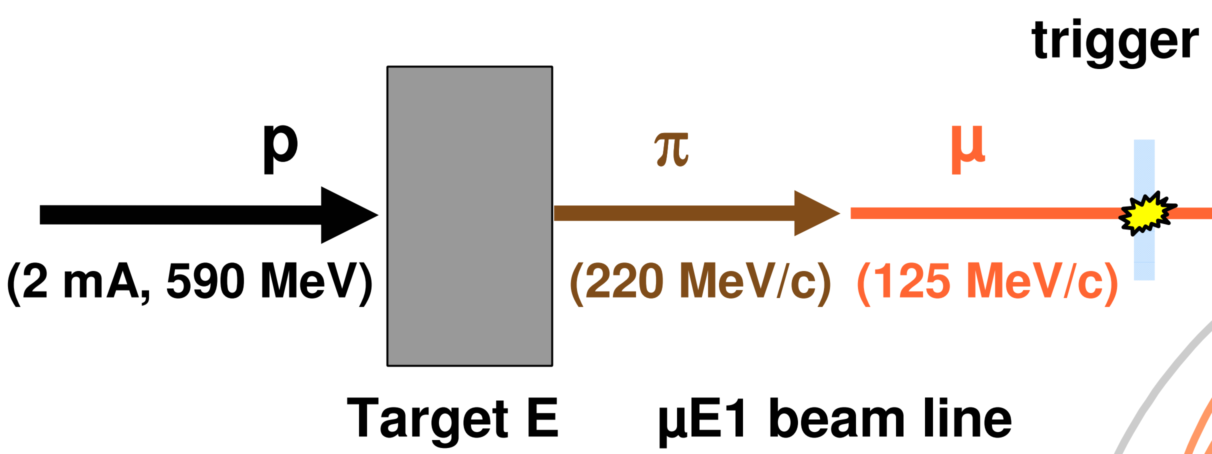
  http://slsbd.psi.ch/pub/slsnotes/tmeta9902/

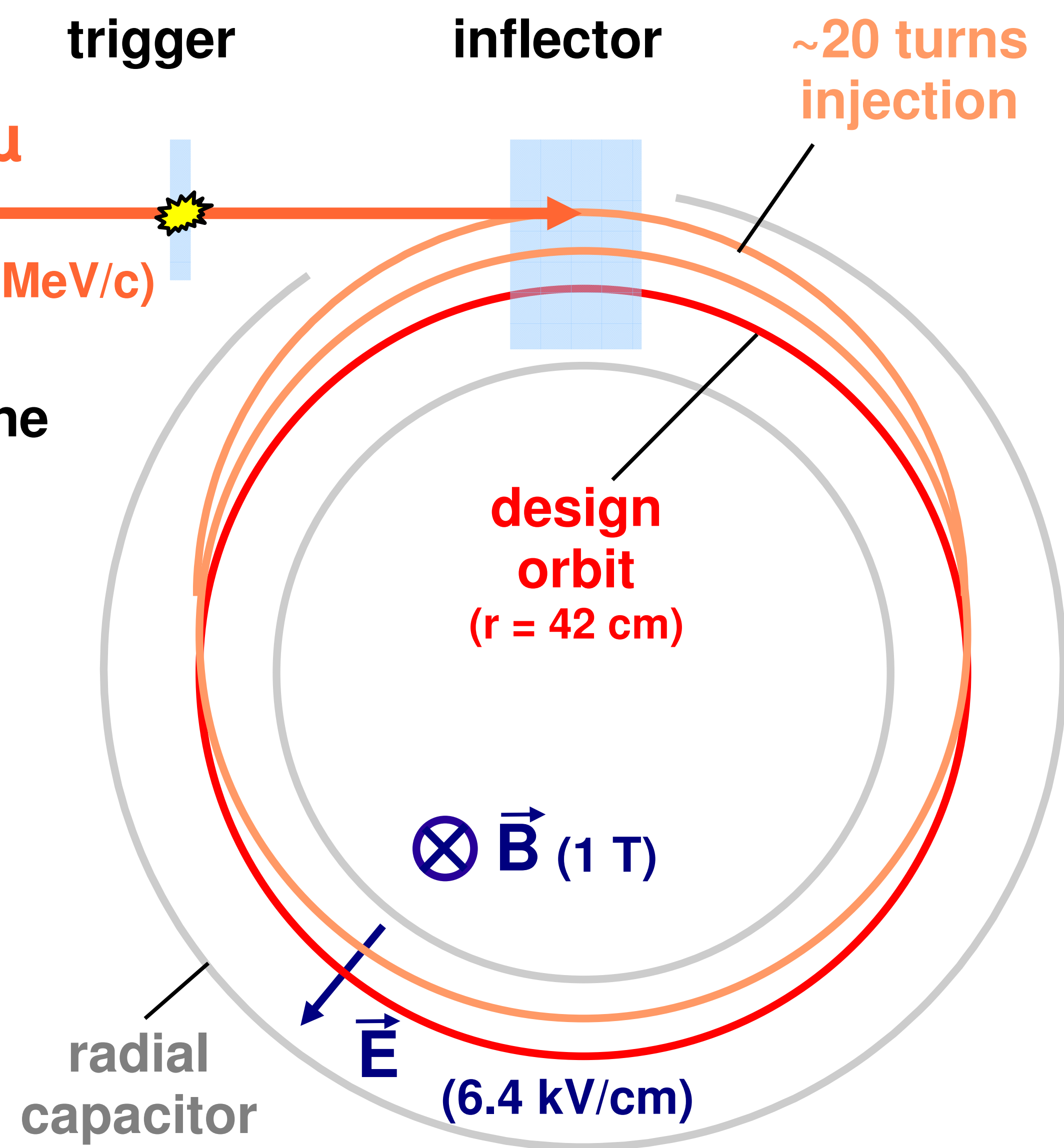
- ***20 turns ramp of non-linear perturbator***
- ***Acceptance ±7 mm / ±11 mrad, average latency for acceptable μ: ~1.2 μs***
- ***Average measurement time $\gamma\tau_\mu$= 3.4 μs***



- ***~200 kHz repetition rate for perturbator***
  - ***Challenging, in particular for "random" ramp-up***
  - ***Can we trigger the perturbator in time to catch the "good" muon?***

Beam schematic





- *Pions produced in thick target*
- *Capture muons from backward decay of pions ⇒ polarized muons (P_{μ} = 92%)*
- *Upon "good muon"-trigger, inflector ramps down non-linear perturbation field over a period of 20 turns*
- *Resonance injection at half-integer*

Various systematics issues...

- **Vertical *E* field** component: $E_\perp < 10^{-4} E_{rad}$.
- Rotational **misalignments** and residual g–2 precession
- **Instabilities** of E, B fields, detector,...

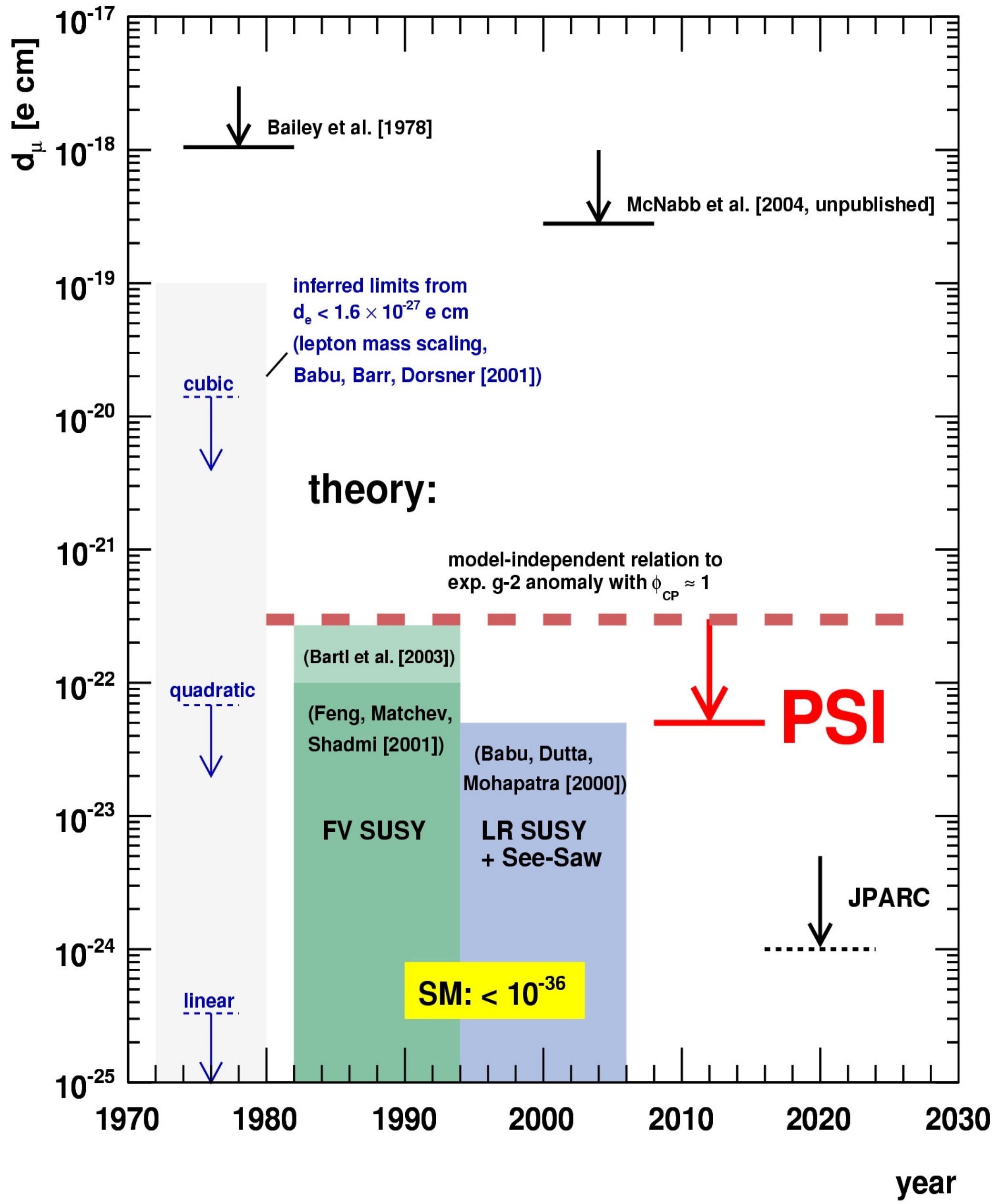
...but many ways to control them:

- Injection of μ^+ and μ^-
  - Factor 3 less statistics for μ^-
- Clockwise and counter-clockwise orbit
- g–2 precession for calibration
- Spin rotation?

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
Phys. Rev. Lett. 93 (2004) 052001

Impact of a PSI measurement

- Rule out (or confirm) EDM explanation for Brookhaven MDM anomaly
- Rule out (or confirm) naïve relation between new physics MDM and EDM for the case $\phi_{CP} \approx 1$.
- Explore the region down to 5×10^{-23} e cm
- ... long before J-PARC (or anyone else) can get there.
- Proof of principle for new technique at relatively low cost



Current status of the project

- Paper presenting the compact storage ring method in more detail is in preparation (follow-up of arXiv:hep-ex/0606034).
- **Poster presentation** at PSI workshop (pmle.web.psi.ch) was **met with enthusiasm:**
  - C. Petitjean: **"the highlight of the workshop"**
  - K. Jungmann: "for just 0.25% of its annual budget, PSI could have a **profound impact on muon physics**"
- PSI management encourages submission of LOI, however clear priority for MEG and nEDM. Need strong external collaborators.
- Strong interest to collaborate from
  - **Boston** (Lee Roberts, see g2pc1.bu.edu/~roberts/muonEDM/index.html)
  - **Groningen** (Gerco Onderwater)
  - Others !?
- Next steps:
  - Look for interested parties world wide
  - With a **proto-collaboration**, envisage writing a **LOI** in 2008.

Thanks …

- for your attention !
- to my collaborators from PSI and Groningen: Andreas Adelmann, Gerco Onderwater, Thomas Schietinger, Andreas Streun
- to Thomas Schietinger who created many of the transparencies; for a longer talk by him, see: http://amas.web.psi.ch/projects/muonedm/
- for various input and fruitful discussions with Francis Farley, Klaus Jungmann, Jim Miller, Lee Roberts, Stefan Ritt, Yannis Semertzidis, …

… and maybe you want to get involved ?

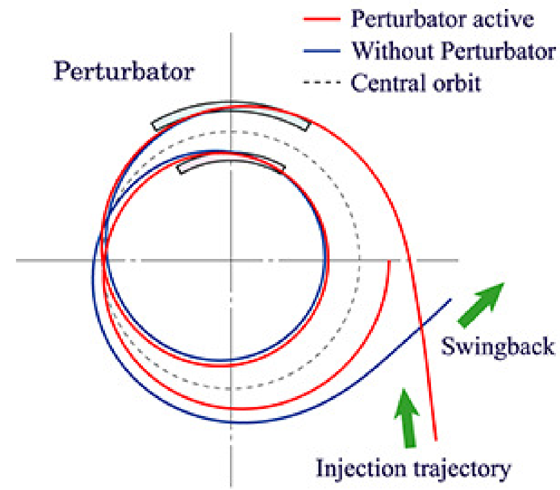
Resonance injection method

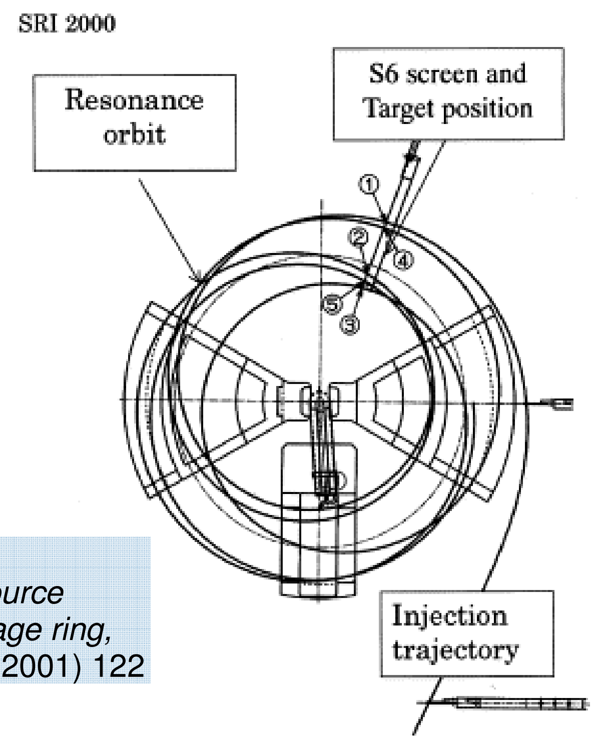
T. Takayama et al.:
Resonance injection method for the compact superconducting SR-ring,
Nucl. Instr. and Meth. A 24/25 (1987) 420

- Developed for injection into commercial ***tabletop synchrotron light-sources***
  - AURORA series (50 cm orbit radius), MIRRORCLE (15.6 cm!) by photon production laboratories, Ltd.

    http://www.photon-production.co.jp/

- ***Perturbator*** excites half-integer betatron resonance (e.g. 3/2), decay to stable orbit over several turns





H. Yamada:
Commissioning of aurora: The smallest synchrotron light source,
J. Vac. Sci. Tehnol. B 8 (1990) 1628

H. Yamada:
Novel X-ray source based on a tabletop synchrotron and its unique features,
Nucl. Instr. and Meth. B 199 (2003) 509

H. Yamada et al.:
Development of the hard X-ray source based on a tabletop electron storage ring,
Nucl. Instr. and Meth. A 467/468 (2001) 122