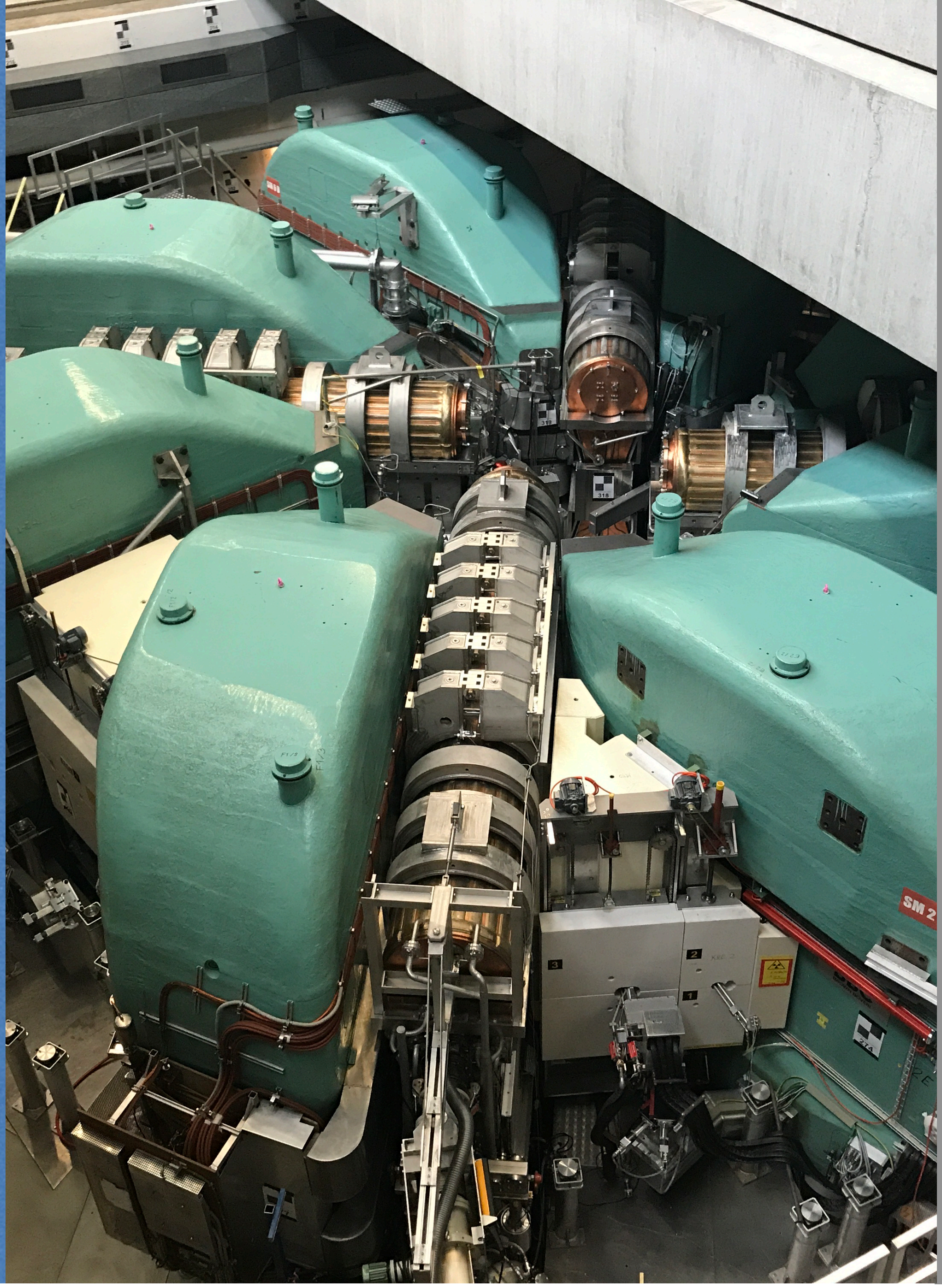
muEDM:

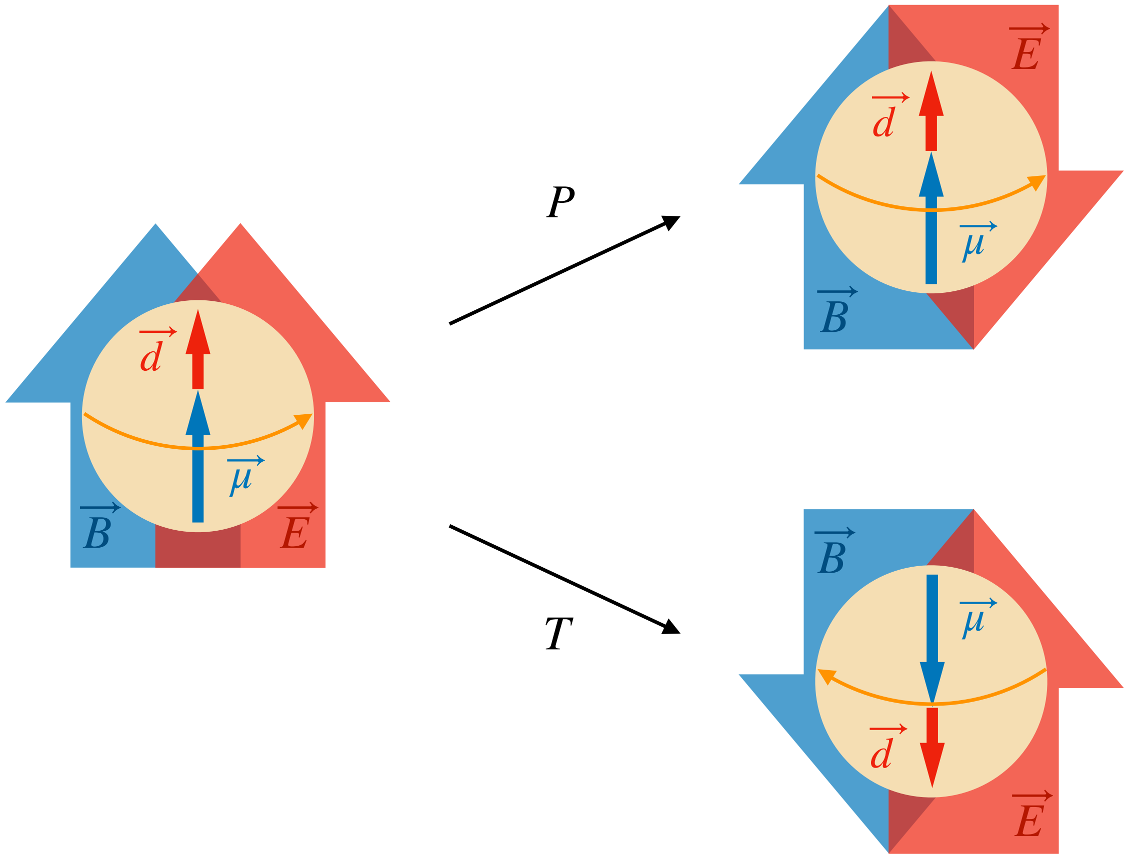
Towards a search for the muon electric dipole moment at PSI using the frozen-spin technique



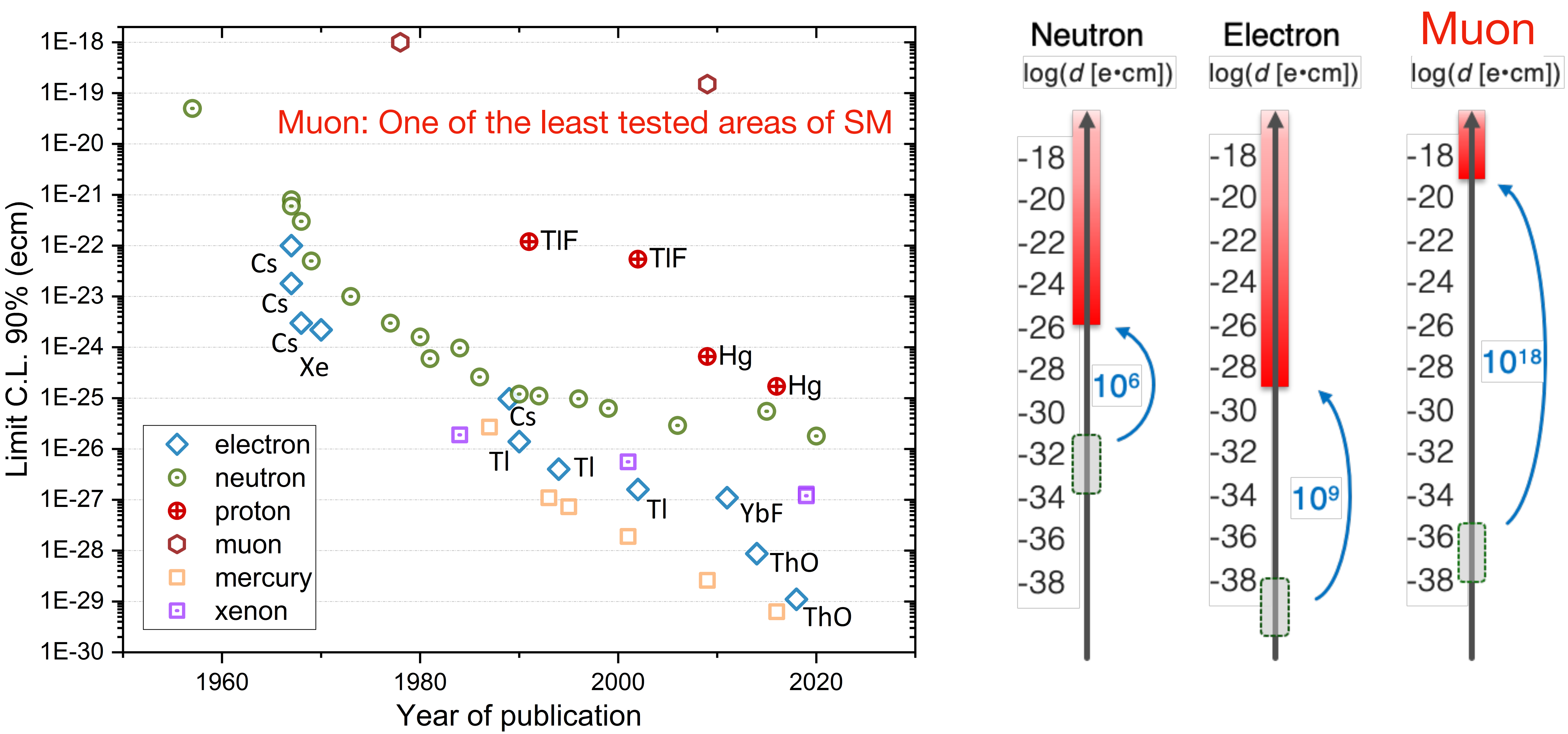
Mikio Sakurai
on behalf of the muEDM initiative at PSI
ETH zürich / PAUL SCHERRER INSTITUT PSI
msakurai@phys.ethz.ch

EDM and CP violation

- In the presence of magnetic and electric fields, the interaction Hamiltonian is $H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$
- A non-zero particle EDM violates P and T
- Assuming CPT invariance, T violation implies CP violation
- Non-zero EDM detection indicates new source of CP violation from BSM
→ Could provide an explanation for the matter-dominated Universe

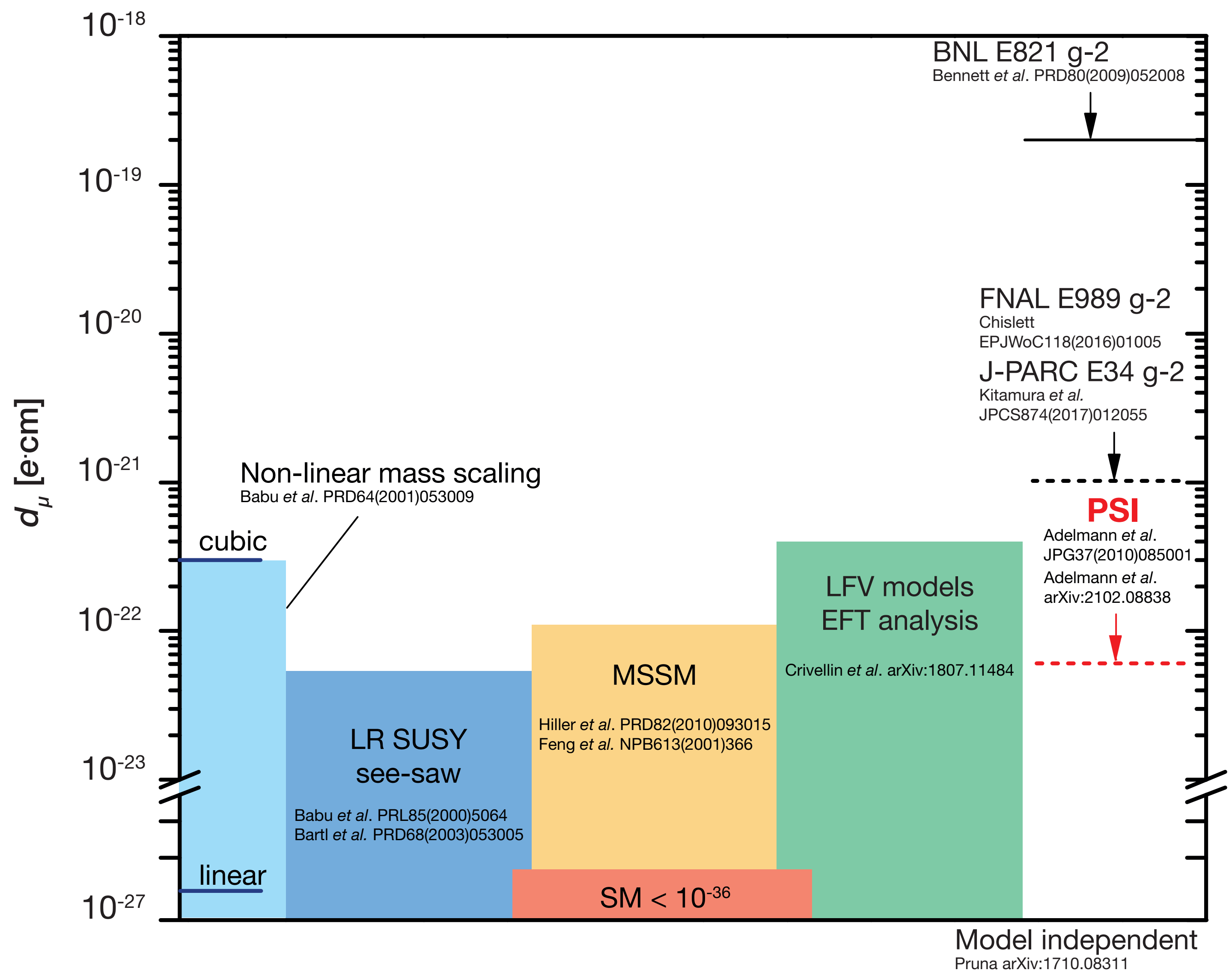


Status of EDM searches



Motivation of muon EDM search

- Muon EDM always has been measured as a by-product in the g-2 storage ring
- Current limit from BNL g-2:
  $d_\mu < 1.8 \times 10^{-19} e \cdot \mathrm{cm}$ (95 % C . L.)
- Linear mass scaling with electron EDM limit:
  $d_e \sim 10^{-29} e \cdot \mathrm{cm} \rightarrow d_\mu \sim 10^{-27} e \cdot \mathrm{cm}$
- However, BSM theories allow a larger value:
  d_μ could be as large as $\sim 10^{-22} e \cdot \mathrm{cm}$
- Moreover, observed tensions with the SM
  - *B*-decays at LHCb
  - 4.2σ deviation in muon g-2
- Muon EDM can
  - further push EDM searches beyond to 1st generation particles
  - probe the role of the lepton flavour universality



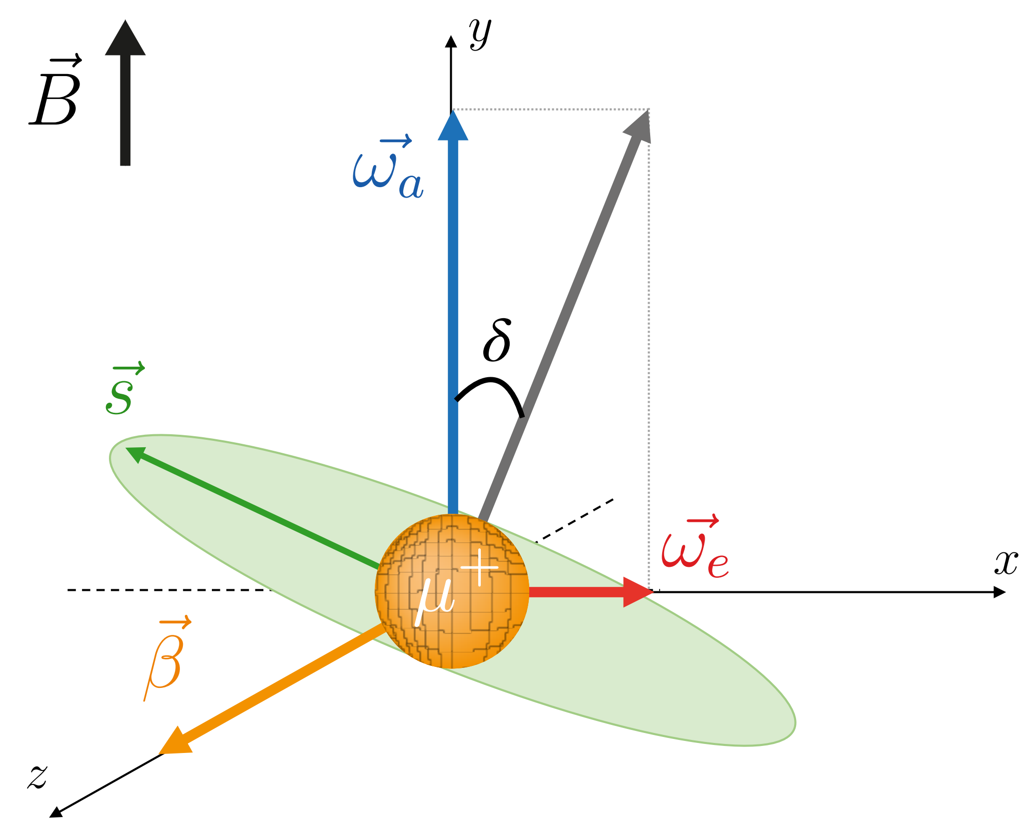
electron EDM: ACME Collaboration, Nature 562 (2018) 355-360

Muon spin precession in E- and B-fields

AMM **EDM**

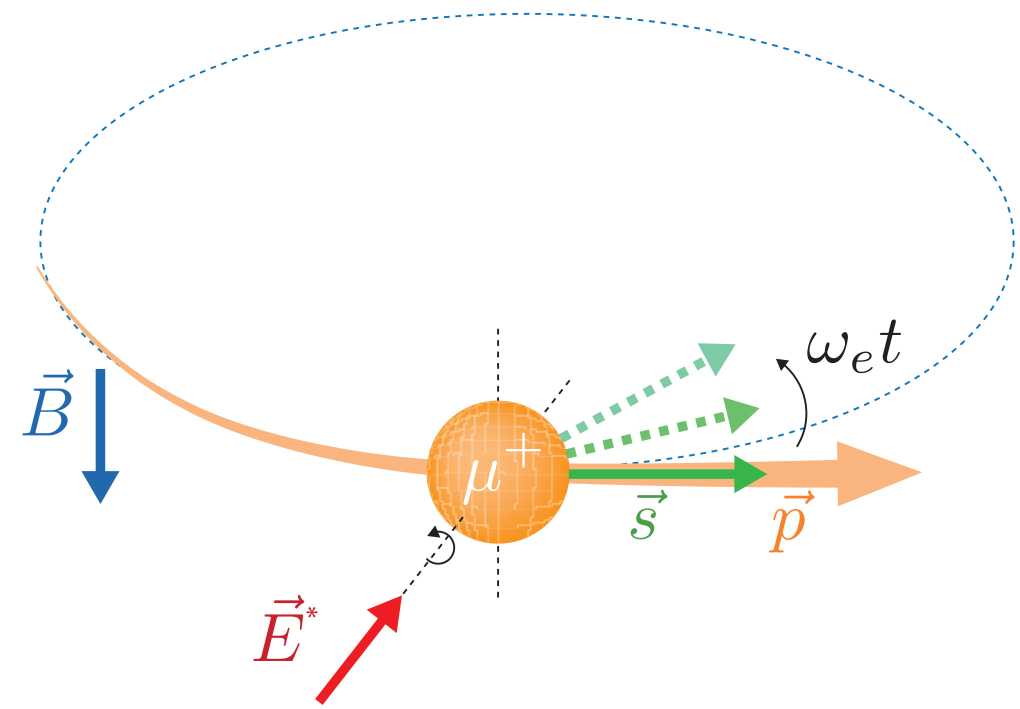
$$\frac{d\vec{s}}{dt} = \underbrace{-\frac{e}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\vec{\omega}_a} + \underbrace{\frac{e}{m}\left[-\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]}_{\vec{\omega}_e}$$

- $\vec{\omega}_a$: spin precession in orbital plane ("g-2" precession)
- $\vec{\omega}_e$: spin precession out of orbital plane ("EDM" precession)
- EDM causes very tiny tilt of the precession plane $\delta \sim$ mrad for $d_\mu \sim 10^{-19} e\cdot\mathrm{cm}$
- Challenging to measure this tiny angle for detectors
- New idea: Frozen-spin technique



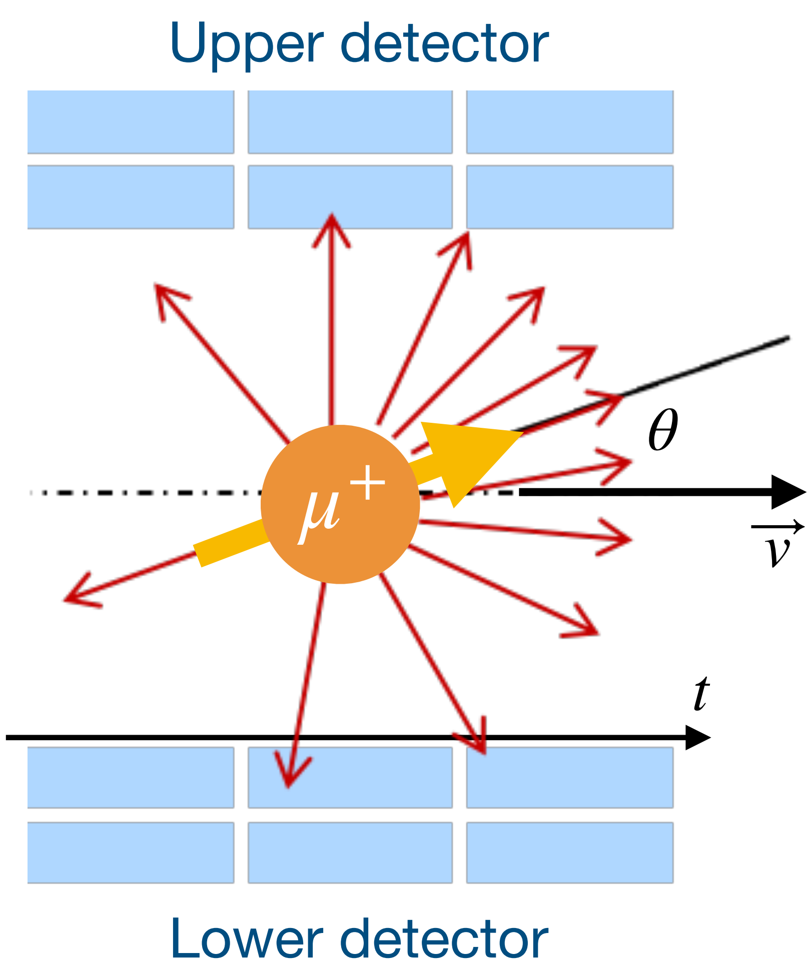
$$\frac{d\vec{s}}{dt} = \overbrace{\underbrace{\cancel{-\frac{e}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}}_{\vec{\omega}_a = 0}}^{\textbf{AMM}} + \overbrace{\underbrace{\frac{e}{m}\left[-\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]}_{\vec{\omega}_e}}^{\textbf{EDM}}$$

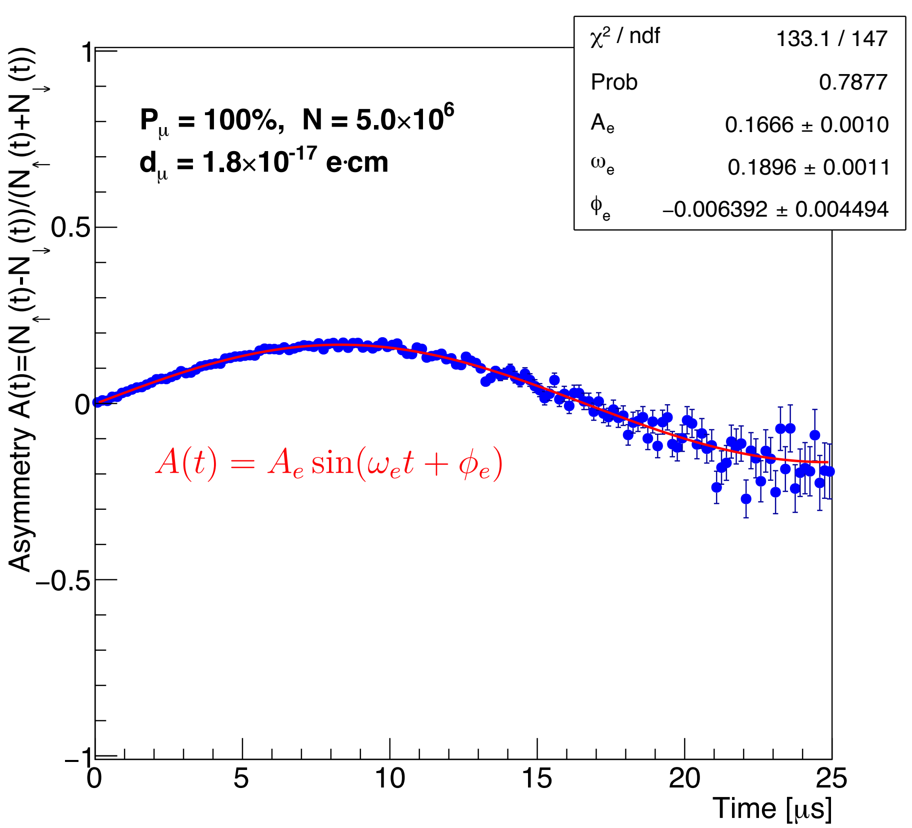
- Cancel “g-2” precession by applying a radial E-field of $E \approx aBc\beta\gamma^2$
- Spin remains parallel on the orbit
- EDM signal is visible as growing vertical polarisation with time



EDM signal

- Up-down counting asymmetry of the muon decay positrons is measured with positron tracker





The initial slope gives the sensitivity of the measurement:

$$\sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0 E_f \sqrt{N}\tau_\mu A}$$

P_0 : Initial polarisation

E_f : Frozen-spin E-field

N : Number of positrons

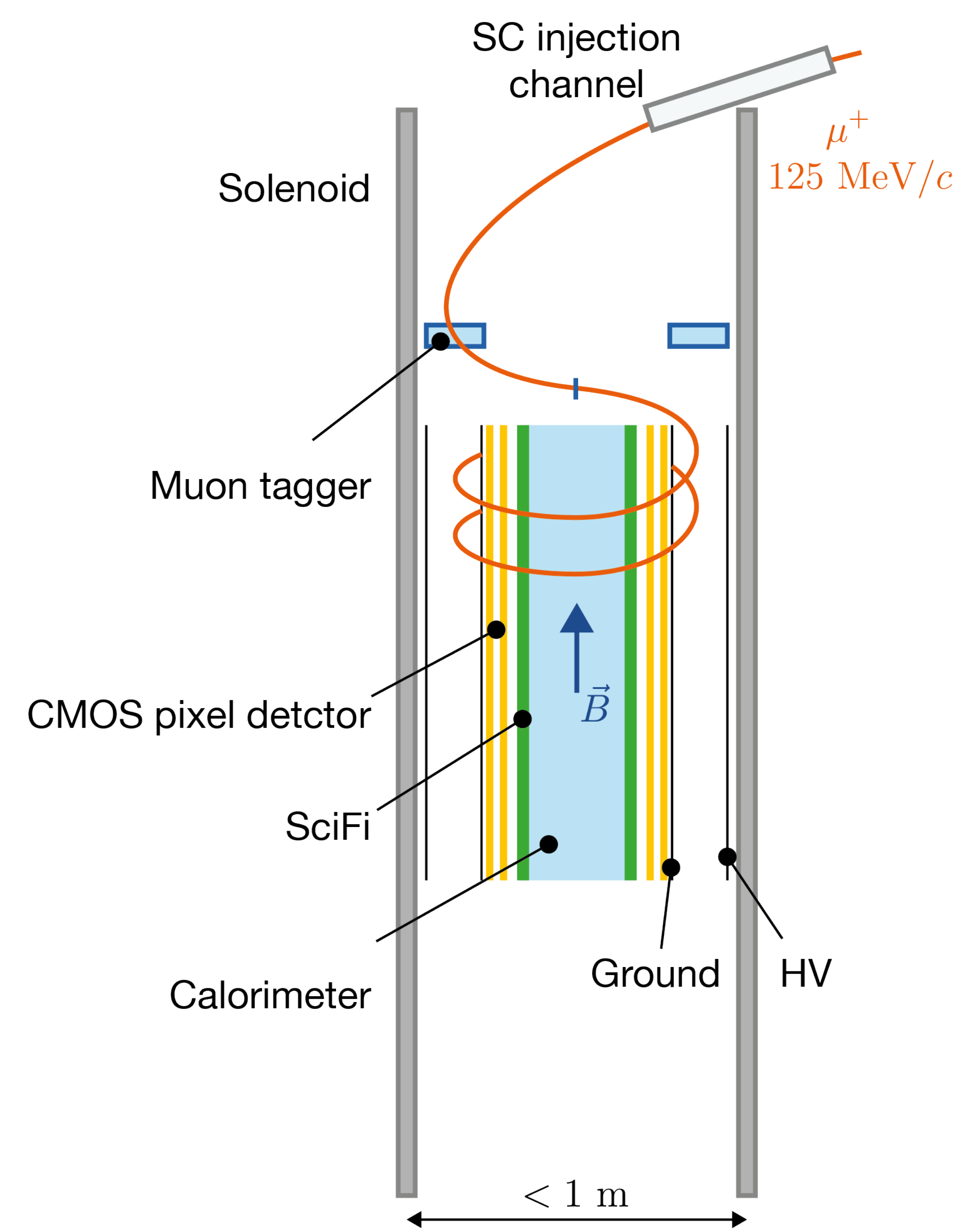
τ_μ : Muon life time

A : Mean analysis power

Concept for muon EDM search at PSI

A. Adelmann *et al.*, JPG 37 (2010) 085001
H. Iinuma *et al.*, NIMA 832 (2016) 51-62
A. Adelmann *et al.*, arXiv:2102.08838 [hep-ex]

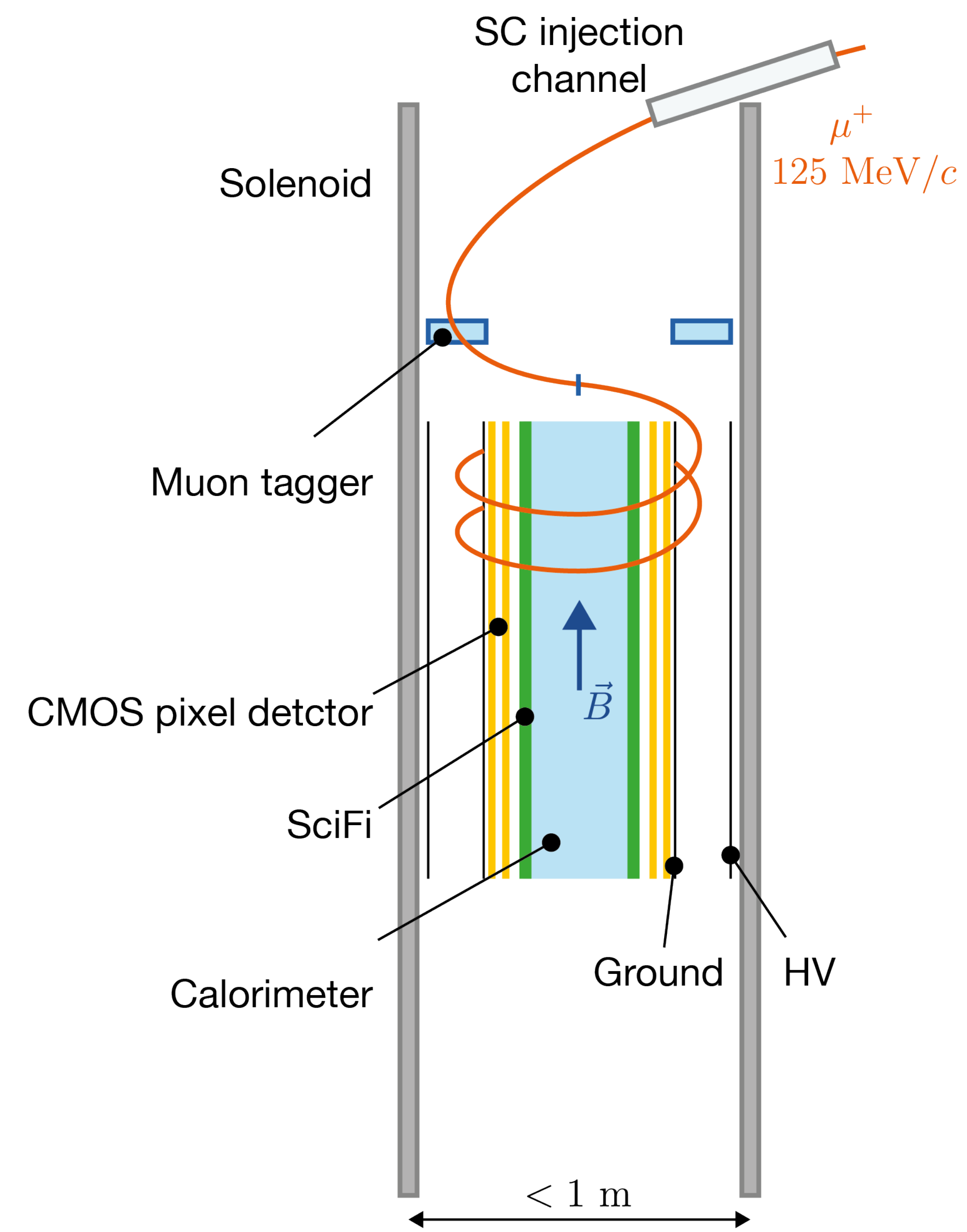
- Original storage ring idea in 2010 + vertical beam injection inspired by J-PARC g-2/EDM
- Vertical beam injection from top into uniform 3 T-field
- Electrodes are far away from injection channel
- Magnetic kicker triggered by fast scintillator signal in SC channel guides muons on to a stable orbit (> 50 ns)
- Store single muon at a time
- Muon tagger for track ID
- Positron tracker made of CMOS pixel detector
- Scintillator gives a fast “end” signal
- Calorimeter for energy resolution



Sensitivity of muEDM experiment at PSI

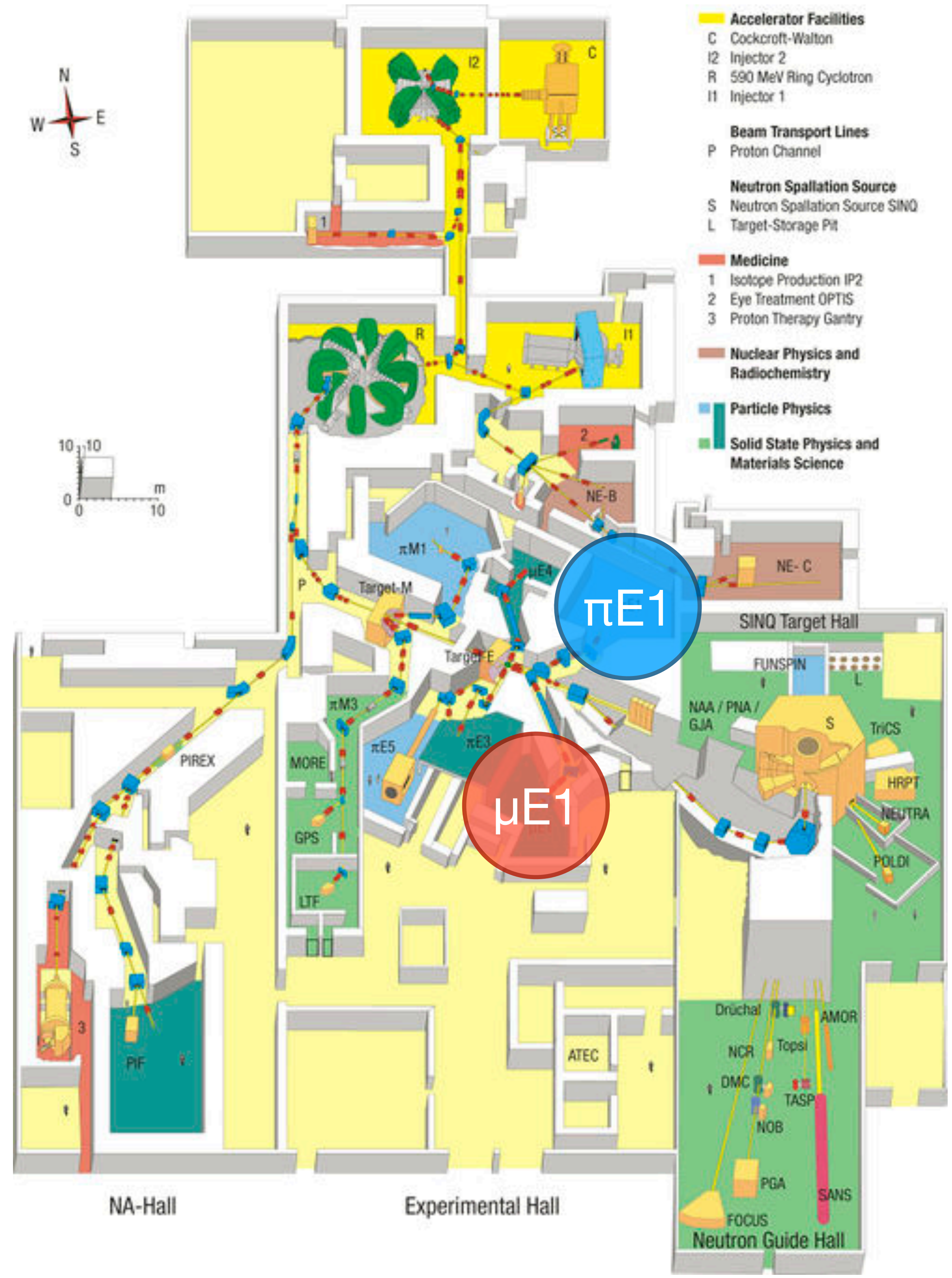
- After 1 year of data taking at PSI μE1 beamline

Gamma factor (p = 125 MeV/c)	γ	1.77
Initial polarisation	P_0	93%
Frozen-spin E-field (B = 3 T)	E_f	2 MV/m
Detection rate		60 kHz
Mean analysis power	A	0.3
#positon detections (200 days)	N	10^{12}
$\sigma = a\hbar\gamma/(2P_0E_f\sqrt{N}\tau_\mu A)$	$<$	$6\times10^{-23}e\cdot\text{cm}$



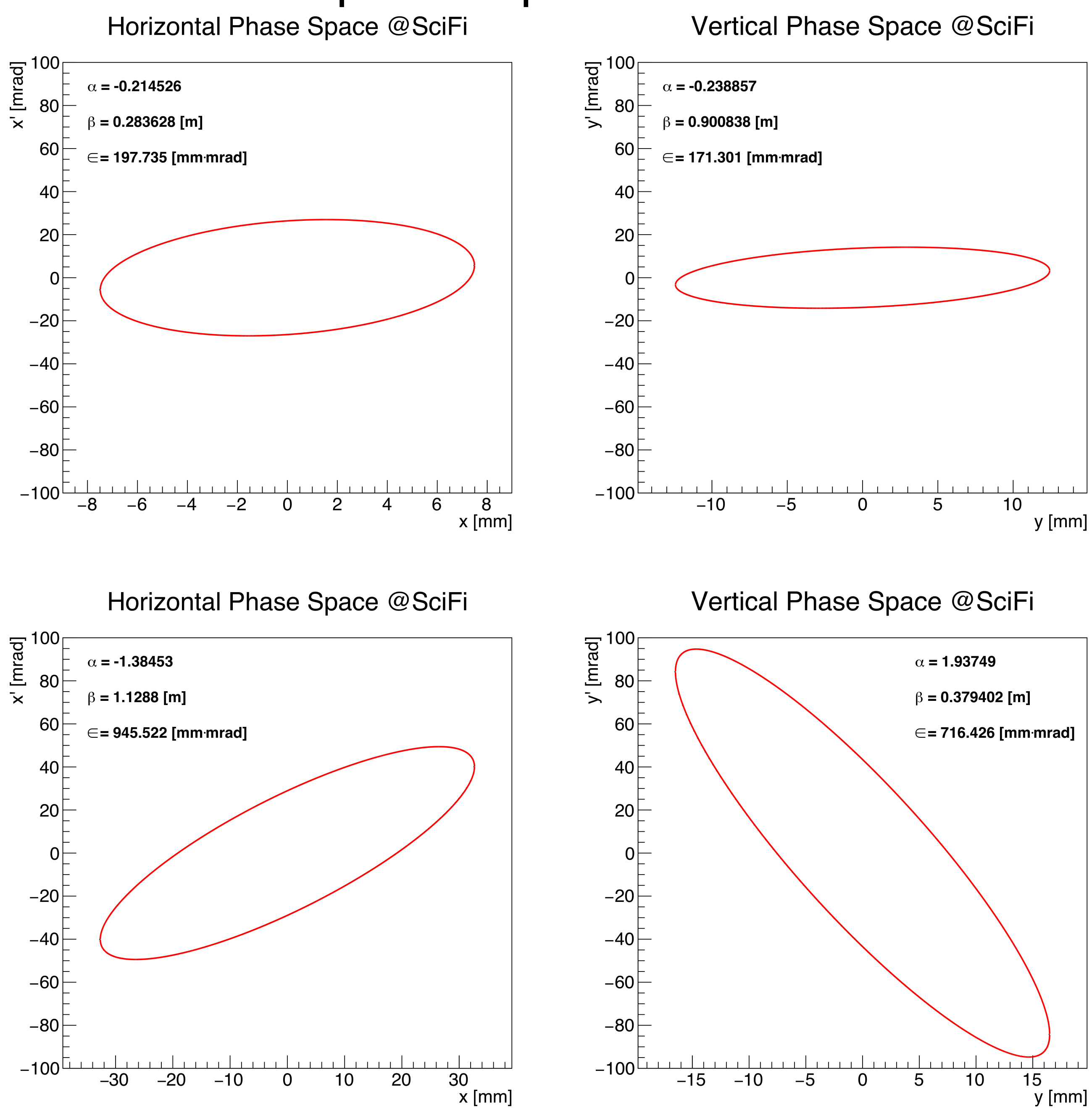
Potential beamlines for the muEDM search

- Possible scenario: 2 phase approach using the same experimental setup
- Phase I: precursor experiment @πE1 beamline
  → Phase II: ultimate sensitivity @μE1 beamline
- πE1 beamline
  - MuSun, muCool, muX
  - Precursor experiment with 28 MeV/c μ^+ beam
    → 10^{-22} e•cm is reachable
- μE1 beamline
  - μSR beamline
  - Final data taking with 125 MeV/c μ^+ beam
- Beamline characterisation was performed in 2019 to obtain input parameters for simulations and injection study



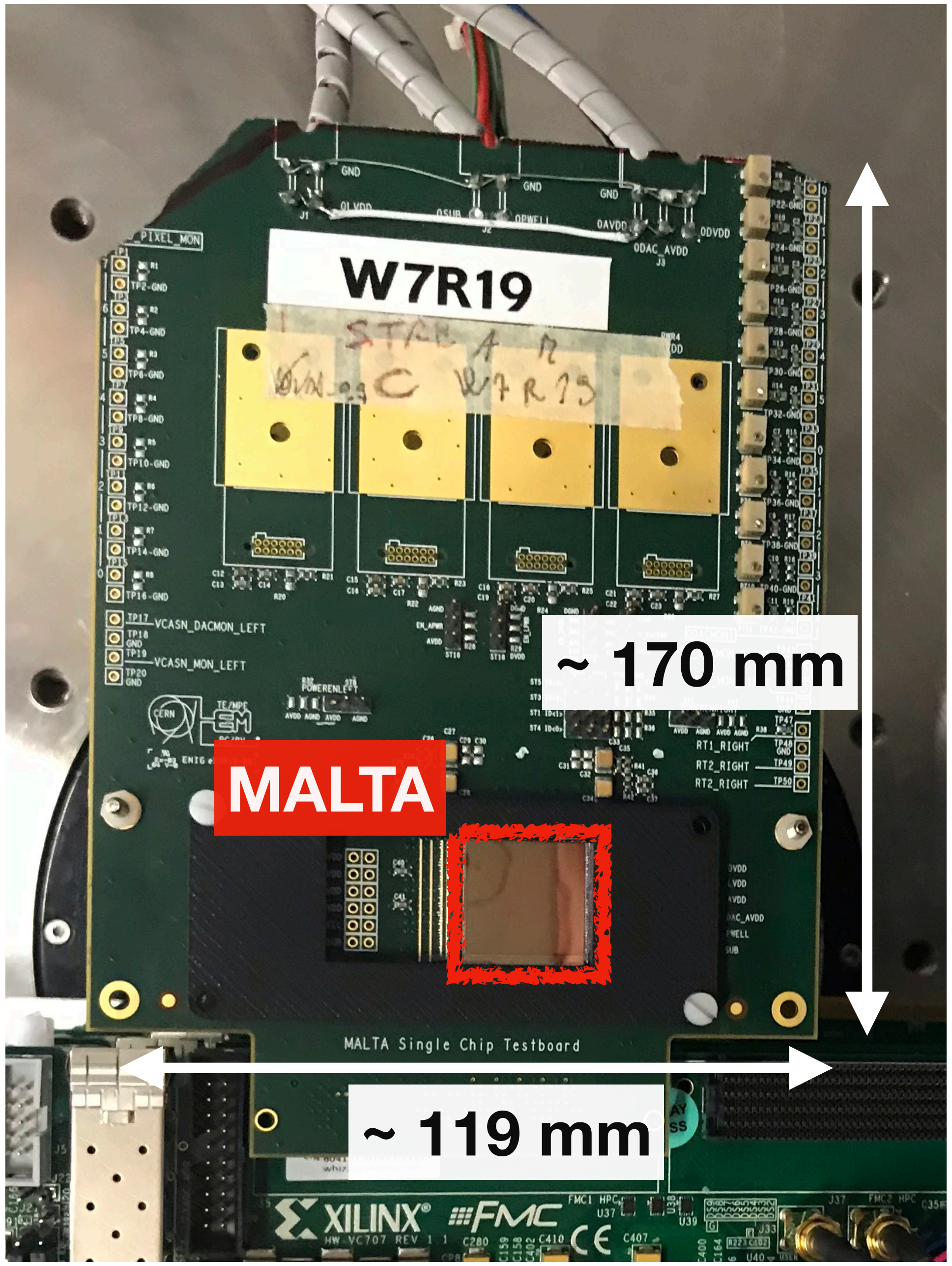
Characterisation of the beamlines

- Quadrupole scan technique was used to determine phase space
- πE1 @28 MeV/c (Precursor)
  - R_μ up to 6.6×10^6 μ^+/s @2.4 mA
  - Emittance (1σ)
    H: 198 mm•mrad
    V: 171 mm•mrad
- μE1 @125 MeV/c (Final data taking)
  - R_μ up to 1.2×10^8 μ^+/s @2.4 mA
  - Emittance (1σ)
    H: 945 mm•mrad
    V: 716 mm•mrad
  - P ~ 93%

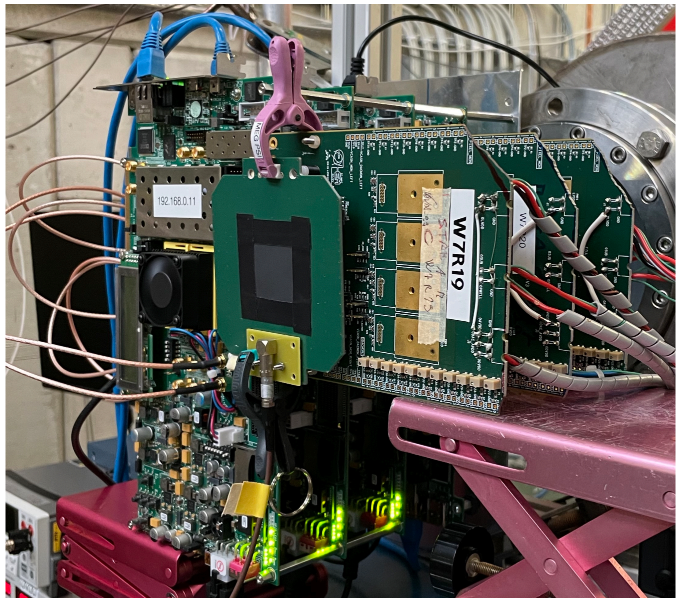


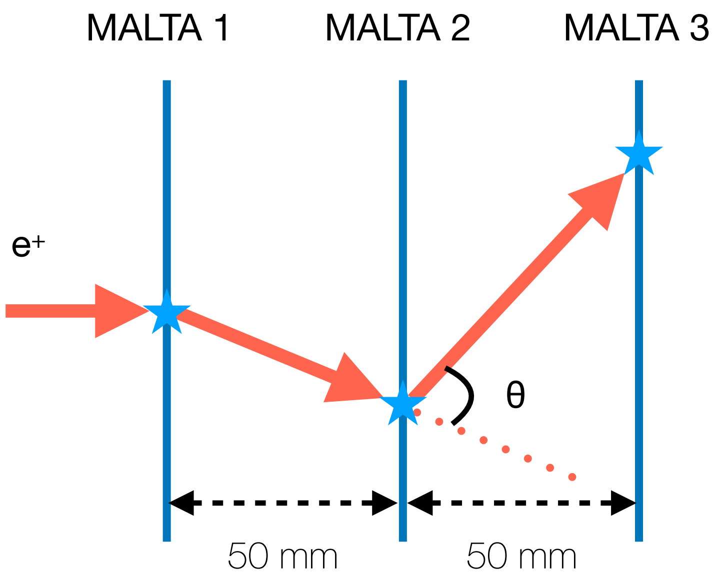
Coulomb multiple scattering study with MALTA

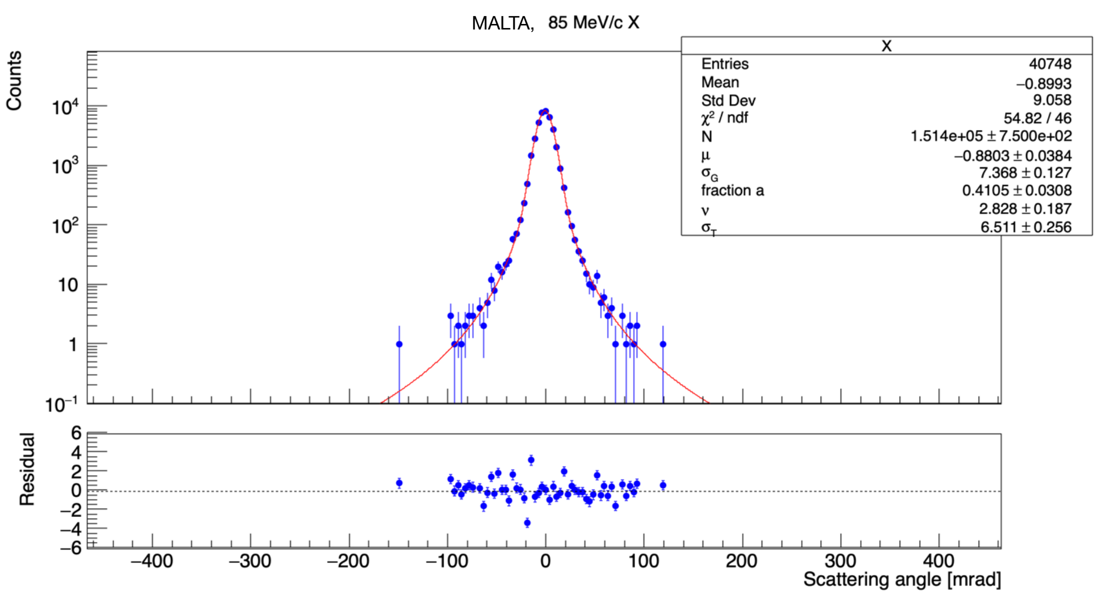
- At low momenta, tracking resolution would be dominated by multiple scattering in materials
- Influence the design of the positron tracking scheme
- Good understanding of the multiple scattering in potential detector materials is important
- MALTA CMOS pixel detector
  - MAPS designed in TowerJazz 180 nm technology
  - Matrix of 512 × 512 pixels
    Pixels of 36.4 × 36.4 μm^2
  - Active area: 18.3 × 18.3 mm^2
  - Our sensor thickness: ~300 μm



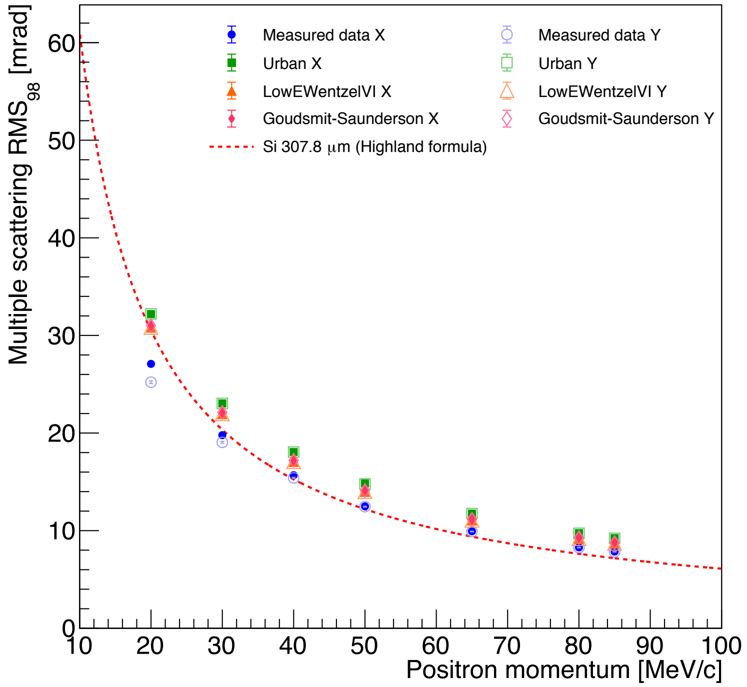
- Studied multiple scattering of positrons at low momenta with using 3-plane MALTA telescope
- e+: 20 - 85 MeV/c
- Measured samples:
  MALTA (Si 307 µm), Kapton/Mylar 500 µm
- Only accept events which has exactly 1 pixel hit per plane and calculate angle based on those 3 points
- A good description of measurements by Geant4 for the RMS of the central 98% of the distribution



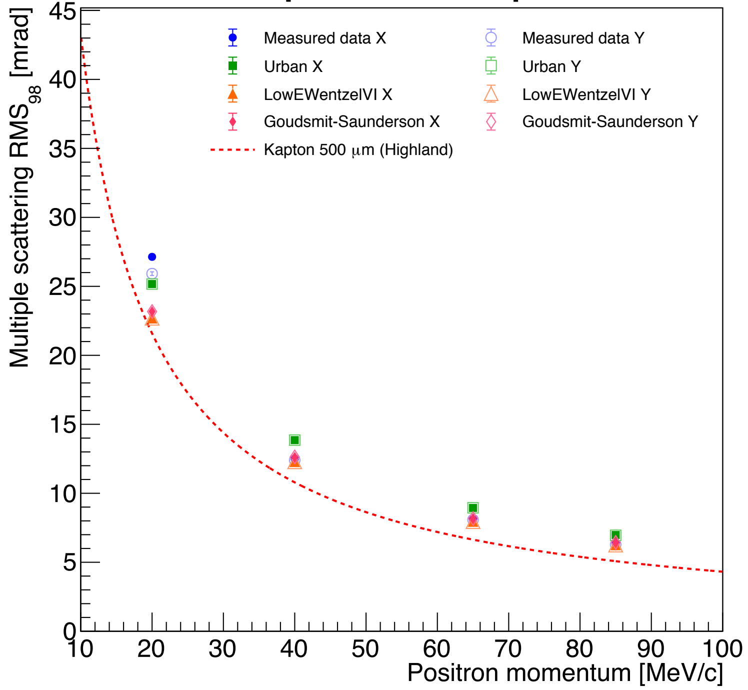




MALTA

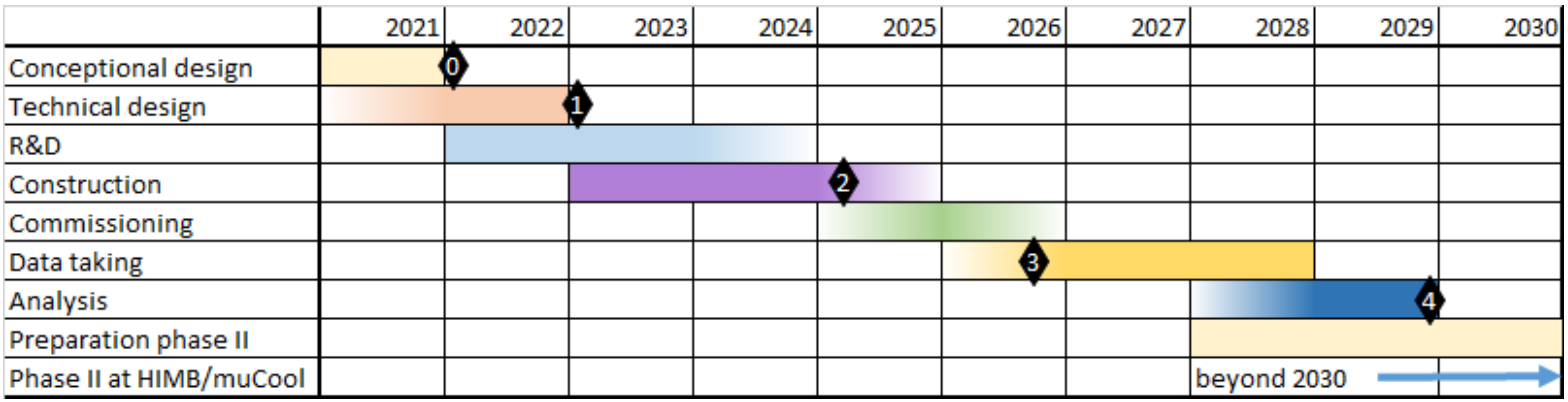


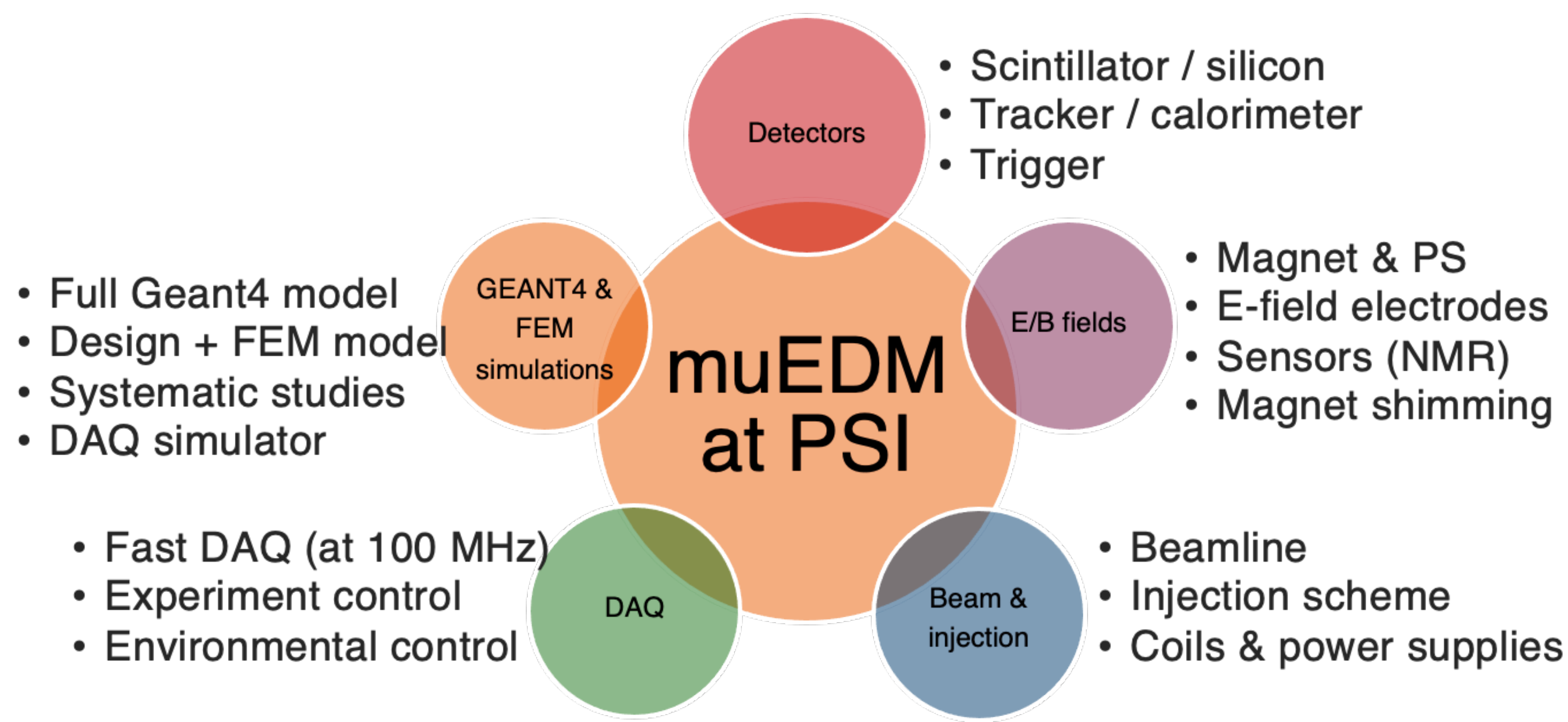
Kapton 500 µm



Tentative schedule

- Several R&D studies are underway for the full experimental proposal submission to PSI
- Aim to start data taking in 2027





Conclusion

- The search for the muon electric dipole moment is a unique opportunity to explore CP violation in BSM physics
- The first dedicated muon EDM search at PSI using the frozen-spin technique aims to achieve a sensitivity of better than $d_\mu < 6 \times 10^{-23} e \cdot \mathrm{cm}$ with existing beamlines
- Several R&D studies are underway at PSI in preparation for the experiment
  - Beam characterisation of the potential beamlines at PSI
  - Study of multiple scattering of positrons at low momenta
- With advent of HIMB and muCool at PSI, an even higher sensitivity can be achieved in Phase II of the experiment

Thank you!

The muEDM initiative at PSI

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] <u>P. Schmidt-Wellenburg</u>,[2] A. Schöning,[22] M. Schott,[4,11] C. Voena,[7,8] J. Vossebeld,[3] F. Wauters,[4] and P. Winter[23]

1 ETH
2 Paul Scherrer Institut PSI
3 University of Liverpool
4 JG|U
5 Université de Genève
6 University of Zurich UZH
7 Sapienza Università di Roma
8 INFN Istituto Nazionale di Fisica Nucleare
9 UCL
10 CERN
11 Cluster of Excellence PRISMA+
12 US University of Sussex
13 tu technische universität dortmund
14 Jülich Forschungszentrum
15 Manchester 1824 The University of Manchester
16 上海交通大學 Shanghai Jiao Tong University
17 李政道研究所 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