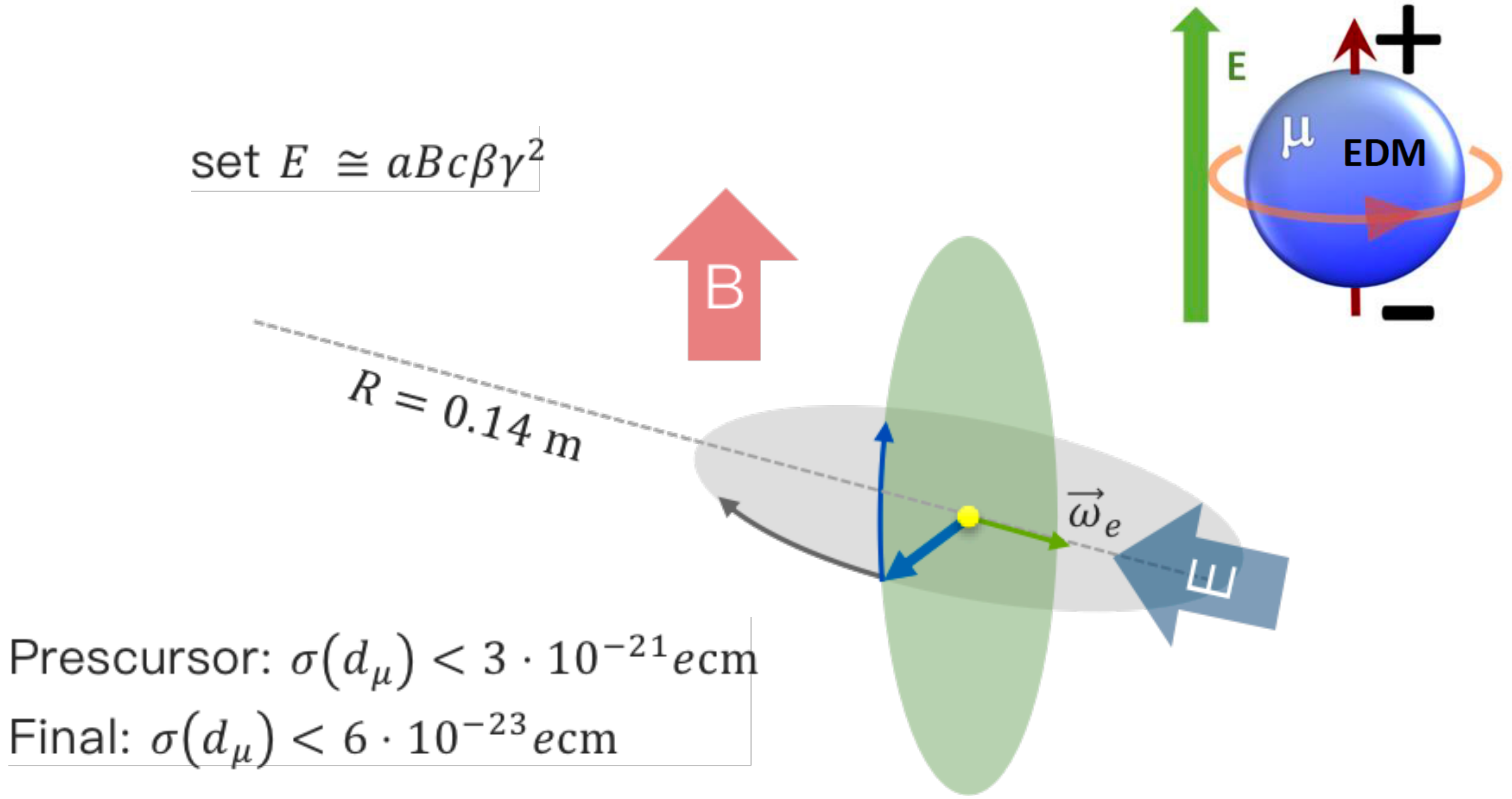
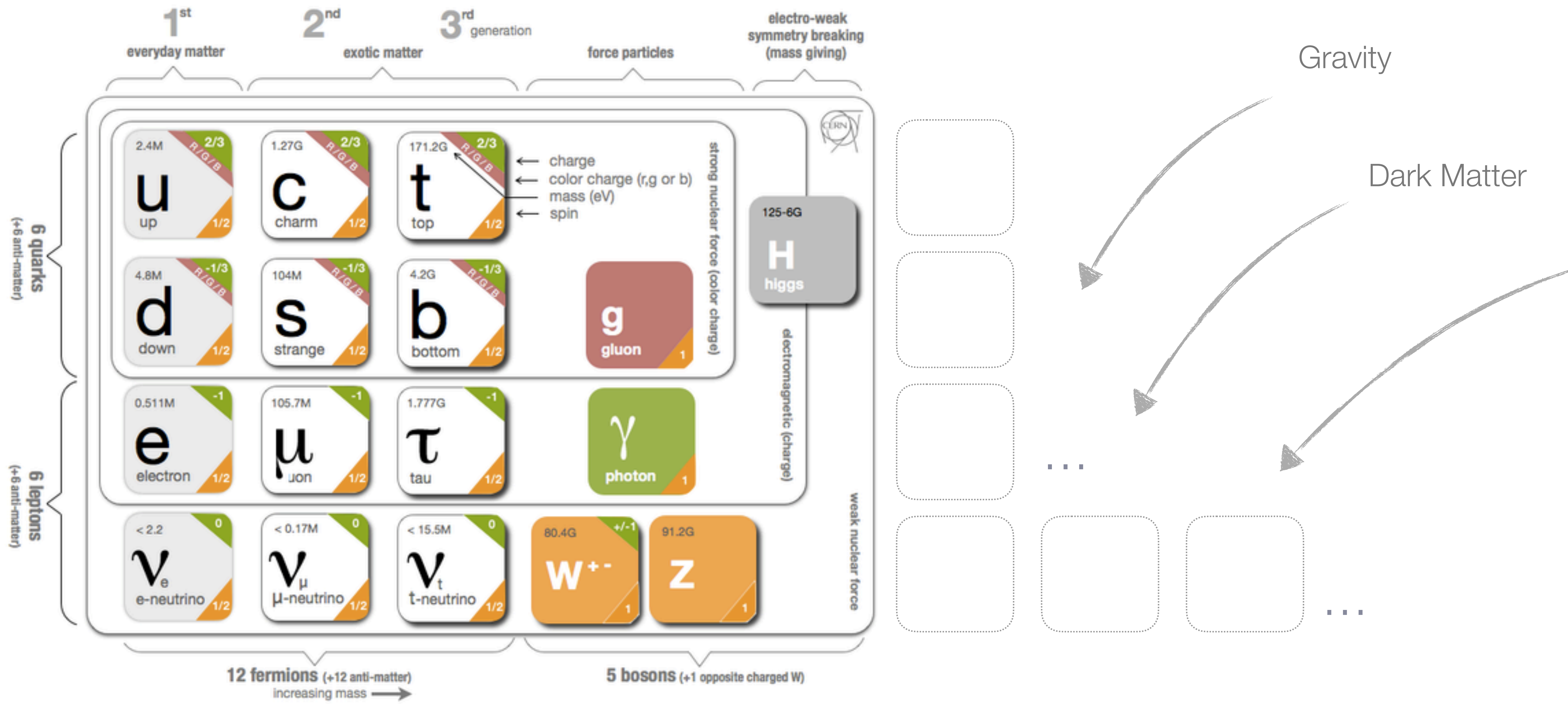
muEDM at PSI: An attractive possibility to extend even further the intensity frontier program

Angela Papa
Snowmass, July 22nd/2022



Motivations: Search for EDMs

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



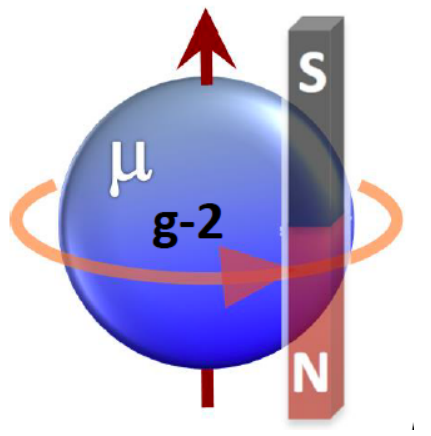
Matter-Antimatter asymmetry

- Baryogenesis, the creation of more matter over anti-matter, requires additional CP violation (CPV) **beyond the SM**
- These **additional CPV** underlying interactions **would also result in Electric Dipole Moments (EDMs)** of fundamental particles at the current experimental sensitivity, **well above** the SM predictions

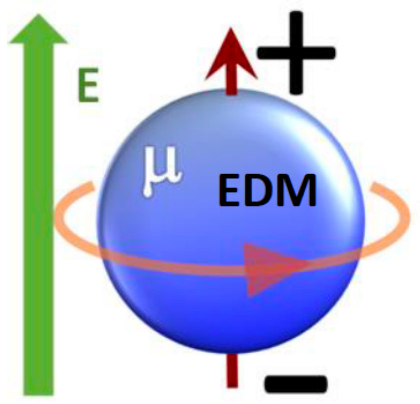
- Low energy precision physics: Rare/forbidden decay searches, **symmetry tests**, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

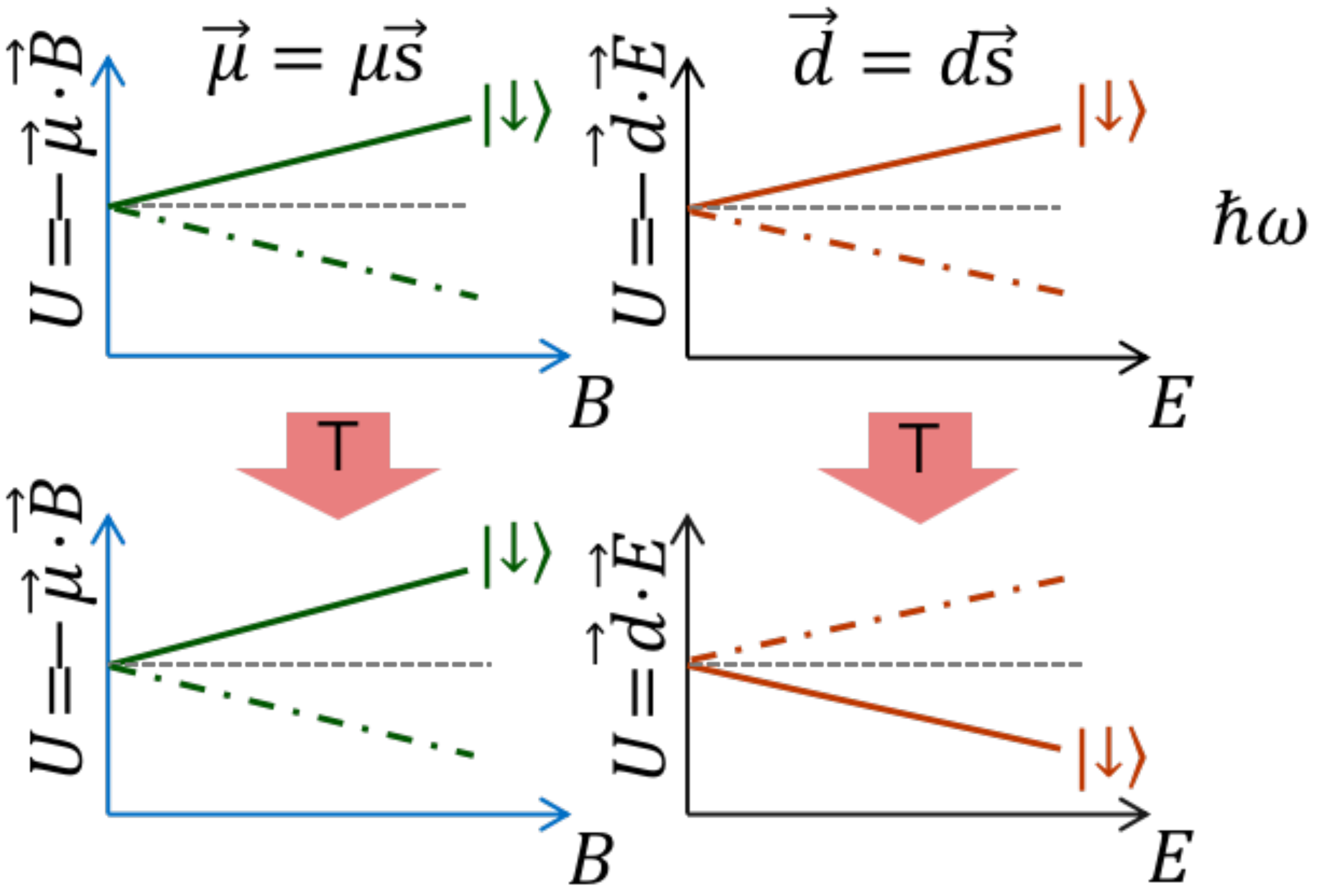
muEDM: Definition

Magnetic moment (**μ** = gqh/4mc **σ**)



Electric moment (**d** = ηqh/4mc **σ**)

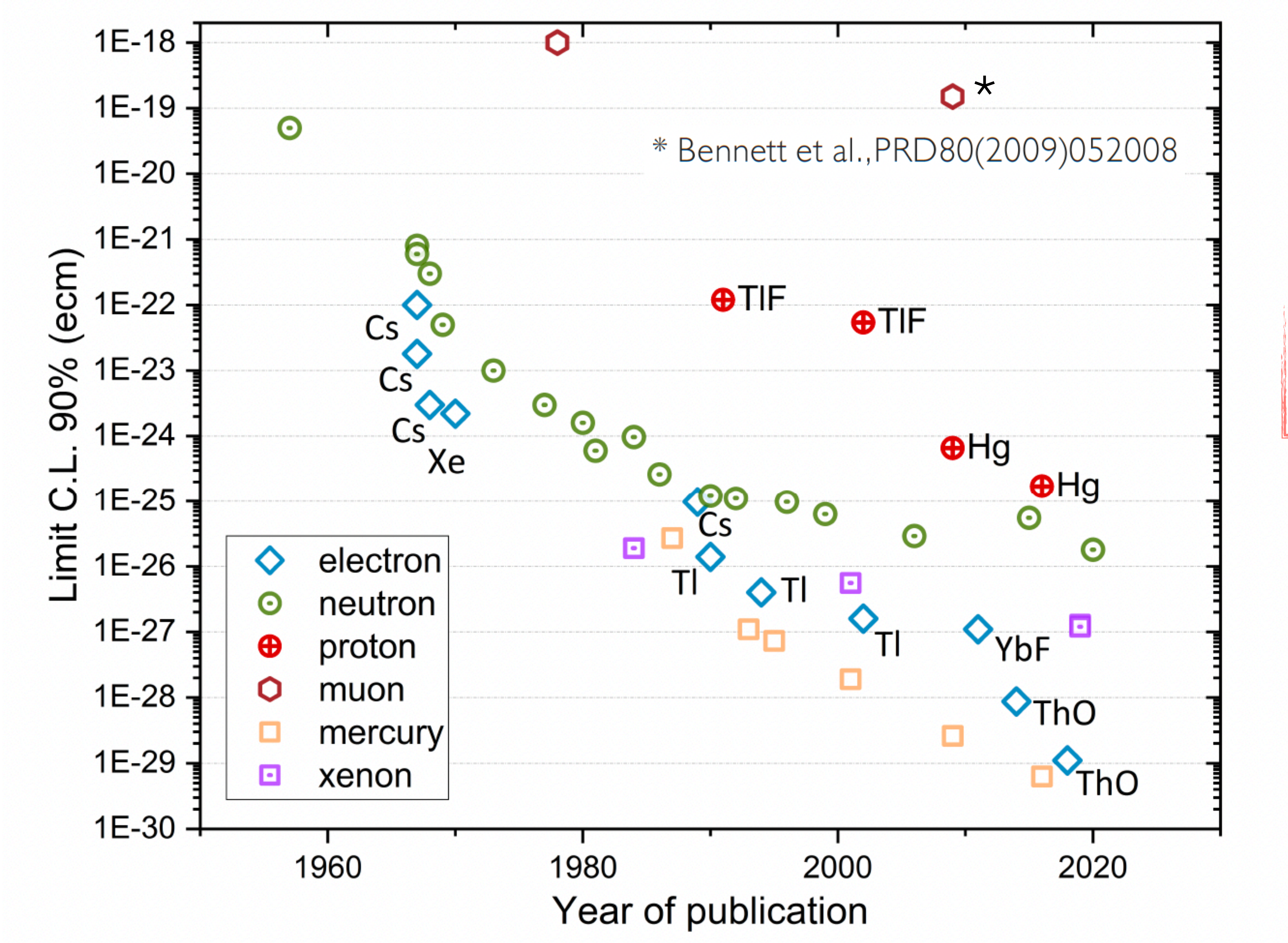




A discovery of a muon EDM indicates CP violation invoking CPT theorem

muEDM dedicated search: Current status

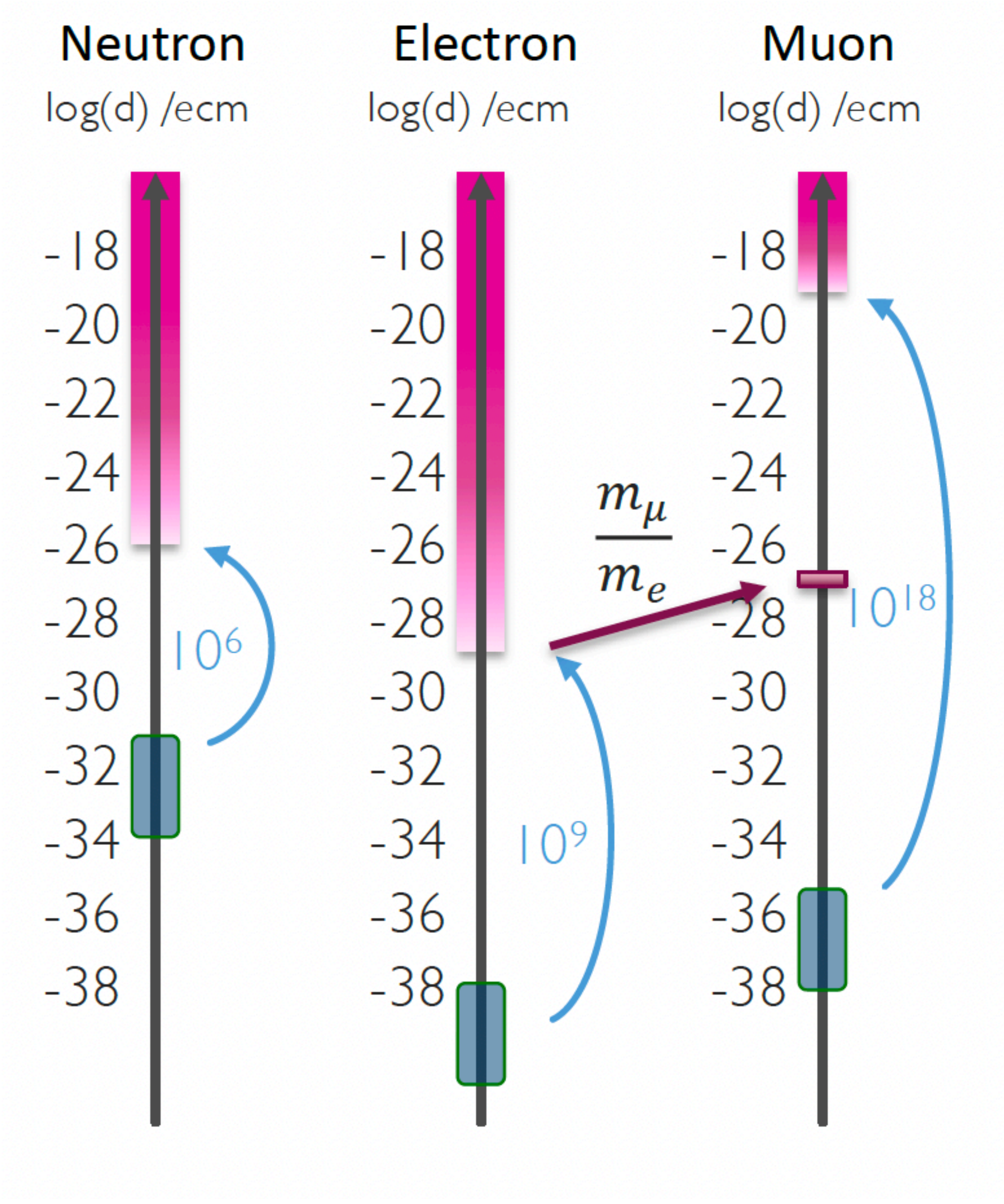
- EDMs of fundamental particles are intimately connected to the violation of time invariance and the combined symmetry of charge and parity
- The different EDM searches are sensitive to different, unique combinations of underlying CPV sources



Quite poor current direct limit

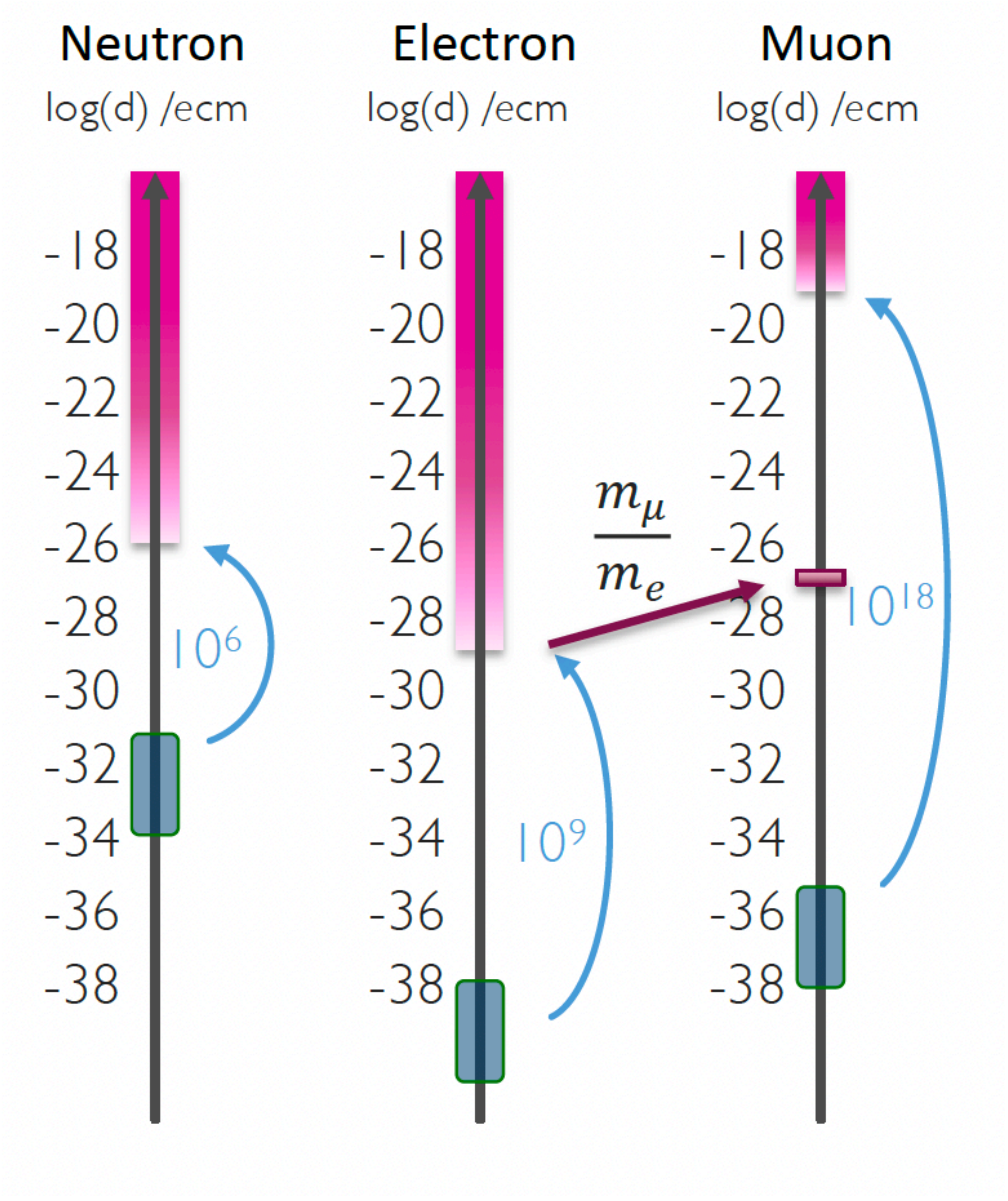
$d_\mu < 1.5\times10^{-19}$ $e$cm **(CL 90%)**

muEDM direct search: Why now?



- Impressive limits on the electron EDM deduced from measurements using atoms or molecules, e.g., thorium oxide molecules $d_e <$ 1.1×10^{-29} ecm (CL 90%) lead to $d_\mu < 2.3\times10^{-27}$ ecm (CL 90%), which is many orders of magnitude better than the direct limit d_μ
  - m_μ/m_e naive rescaling assumes minimal flavor violation (MFV), that is a model dependent assumption
- The **muon plays an exceedingly prominent role in unveiling path towards BSM**. All substantial evidence found in laboratory experiments for a departure from SM physics involves the muon
  - g-2 experiment at FNAL ($a_\mu = (g-2)/2$ —> 4.2σ)
  - LFU in B-meson decays (3.1σ, more than 5σ evidence when combining all LFU observable in B-meson decays)
  - deficit in the 1st row unitarity of the CKM matrix may be interpreted as LFU violation (about 4σ)

muEDM direct search: Why now?



- FNAL/JPARC g-2 experiments aims at $d_\mu \sim \mathbf{O}(10^{-21})$ $e$cm (via g-2)
- **Direct muEDM search at PSI in stages:**
  - **Precursors:** $d_\mu < 3\times10^{-21}$ $e$cm
  - **Final:** $d_\mu < 6\times10^{-23}$ $e$cm

from Paride Paradisi's talk

Few scalings model-independent predictions

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\ell\tau}}{10^{-2}}\right)^2$$

- **EDMs assuming "Naive scaling"** $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-28} \left(\frac{\phi_e^{CPV}}{10^{-4}}\right) e\,\mathrm{cm}\,,$$

$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22}\, \phi_\mu^{CPV}\; e\,\mathrm{cm}\,.$$

- **Main messages:**
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ **requires a nearly flavor and CP conserving NP**
  - **Large effects in the muon EDM** $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ **are still allowed.**

Reminder: g-2 in numbers and experimental approaches

Anomalous magnetic moment (g-2)

a_μ= (g-2)/2 = 11 659 208.9 (6.3) x 10^{-10} (BNL E821 exp) **0.5 ppm**

11 659 182.8 (4.9) x 10^{-10} (standard model)

Δa_μ= Exp - SM = 26.1 (8.0) x 10^{-10} ~4σ **anomaly**

In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0

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

BNL E821 approach
γ=30 (P=3 GeV/c)

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

Continuation at **FNAL** with **0.1ppm** precision

J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

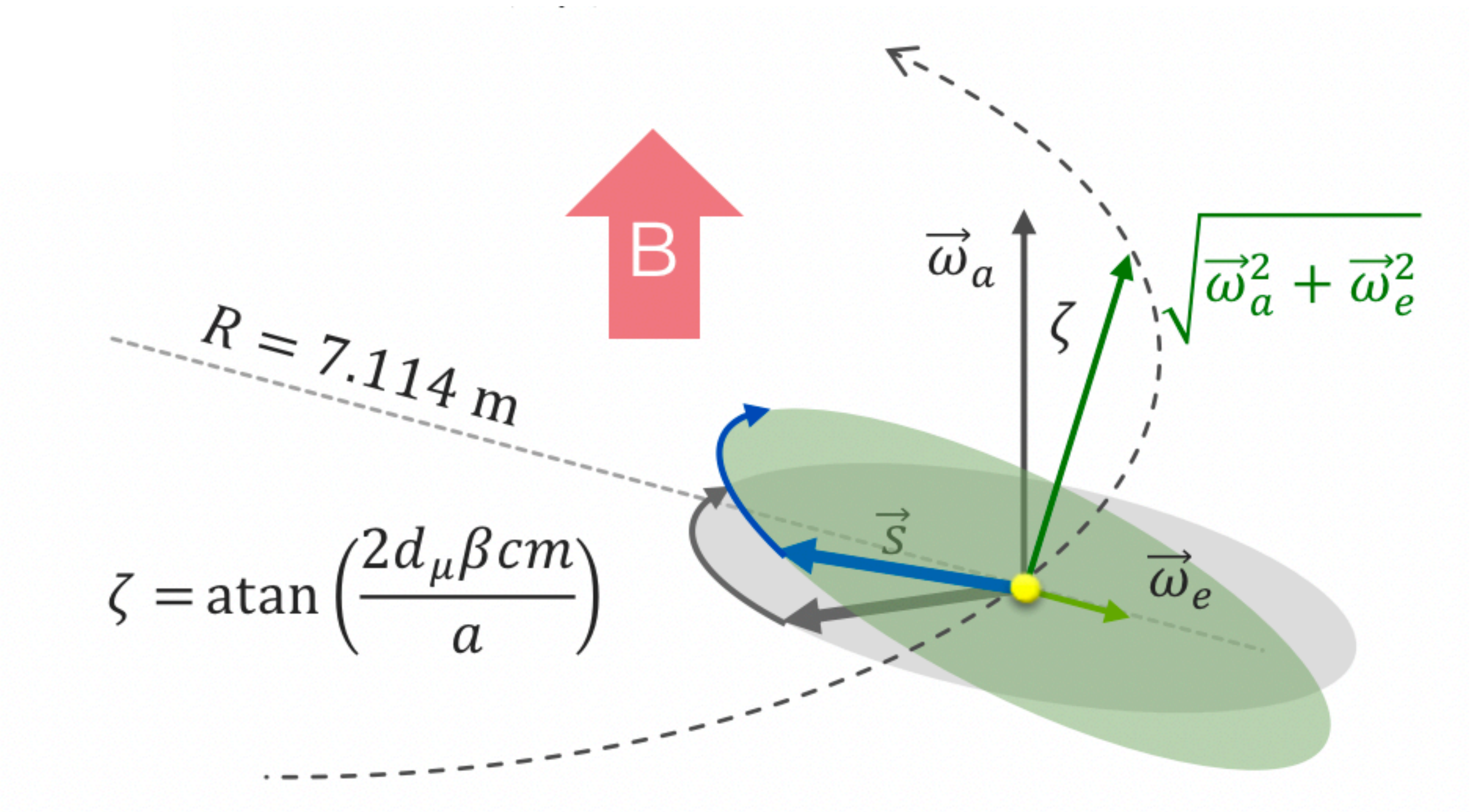
Proposed at **J-PARC** with **0.1ppm** precision

EDM search: From the “frequency” approach…

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

ω_a ω_e

- i.e. FNAL: The decay positrons are recorded using calorimeters and straw tube trackers inside the storage ring
- The sensitivity to a muon EDM is limited by the resolution of the vertical amplitude, proportional to ζ, of the oscillation in the tilted precession plane
- i.e. J-PARC: even if the technique is different the sensitivity to an EDM is limited by the resolution of the vertical amplitude



…to the frozen-spin technique

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

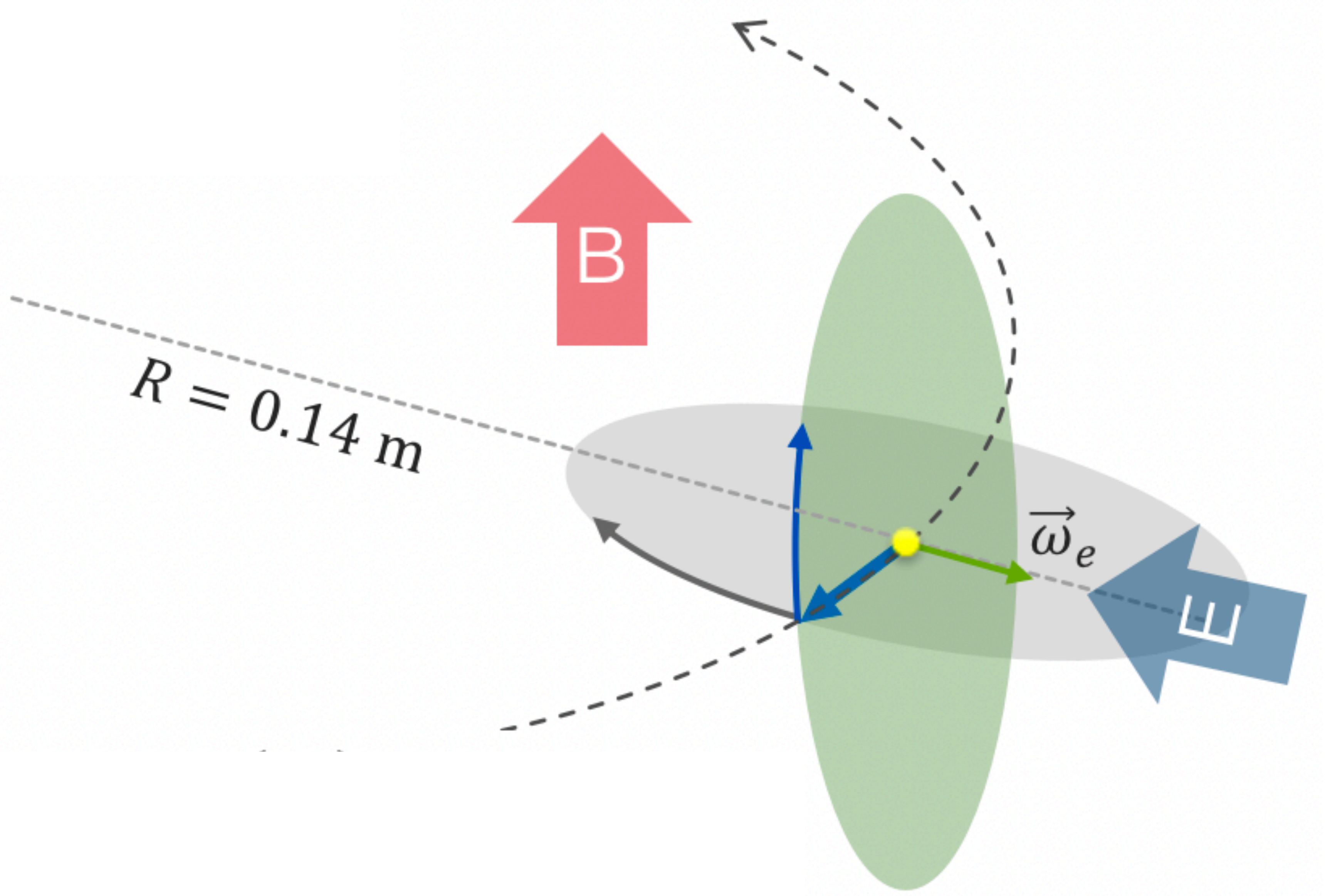
ω_a ω_e

- The frozen-spin technique uses an Electric field perpendicular to the moving particle and magnetic field, fulfilling the condition:

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}_f}{c}$$

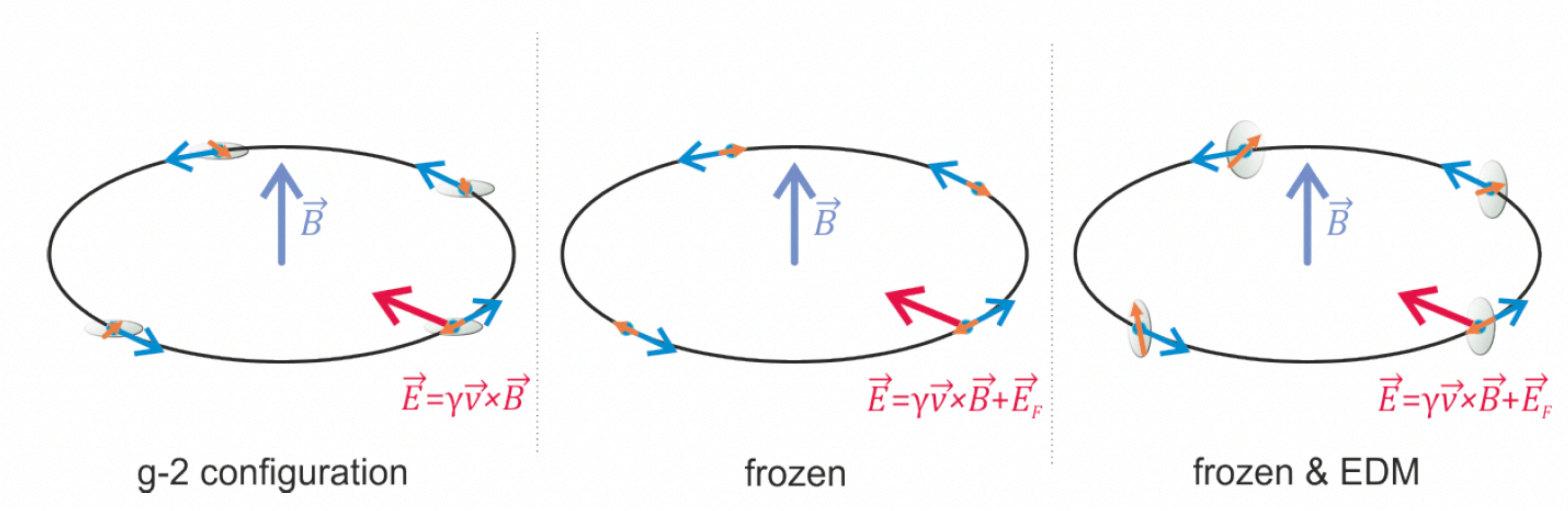
- Without EDM, $\omega = 0$, the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with $\omega_e \parallel E$

- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay



EDM: From the "frequency" approach to the frozen-spin technique

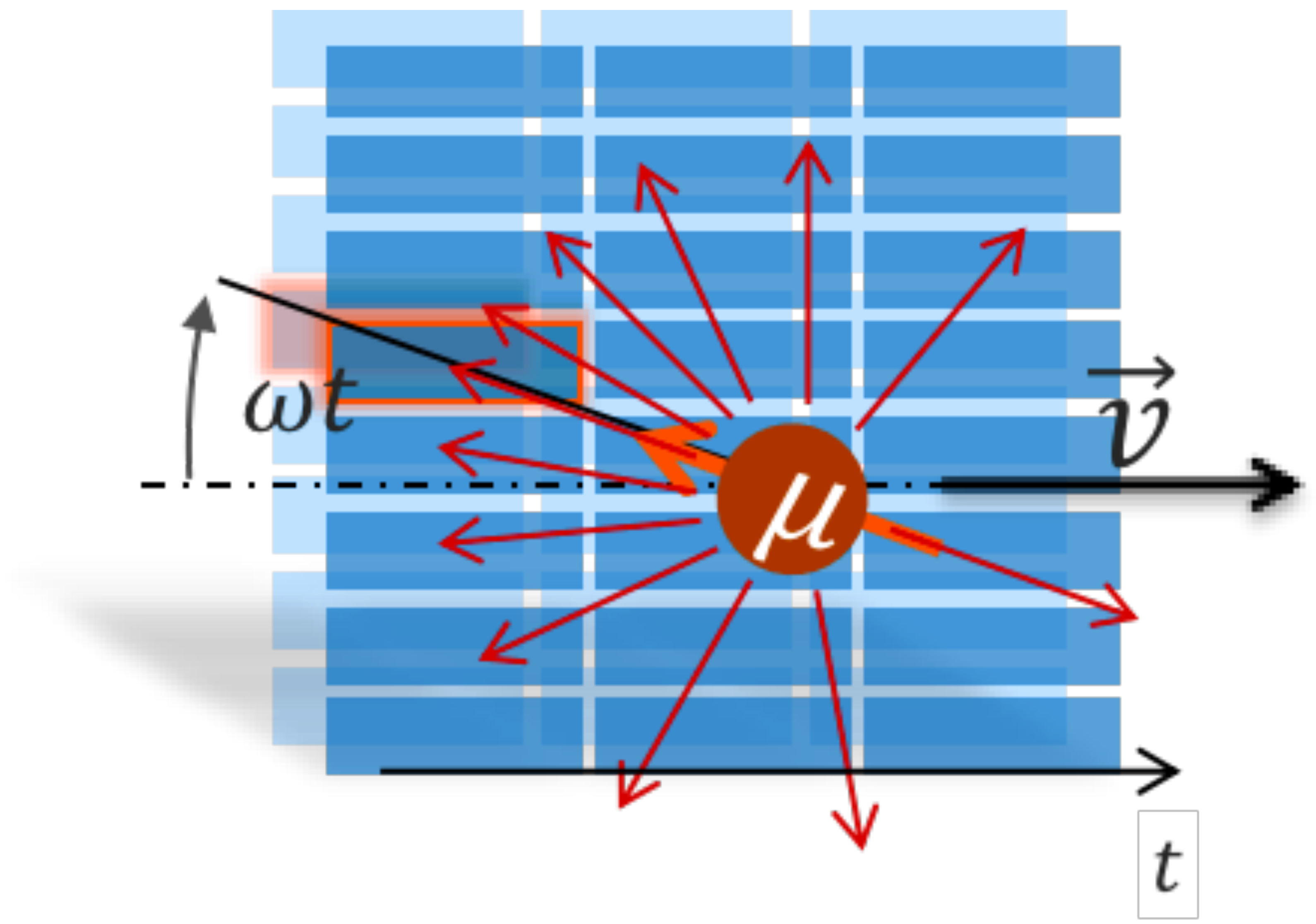
- Putting everything together, here a summary:

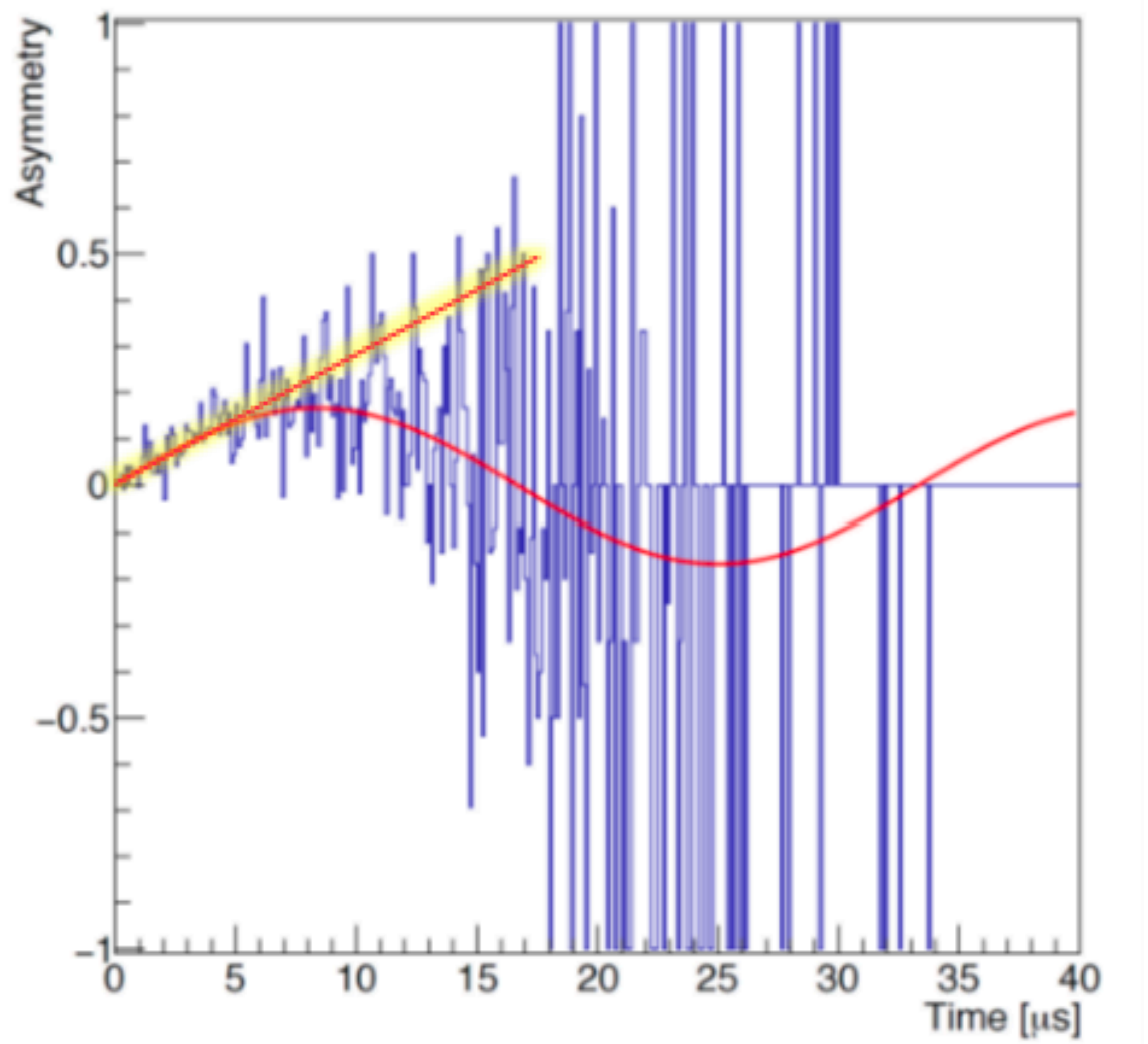


Signal: asymmetry up/down positron tracks

- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay
- Positron are emitted predominantly along the muon spin direction

$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)} = \alpha p \sin\left(\frac{2d_{\mu}}{\hbar}t\right) \approx \alpha p \frac{2d_{\mu}}{\hbar}t$$





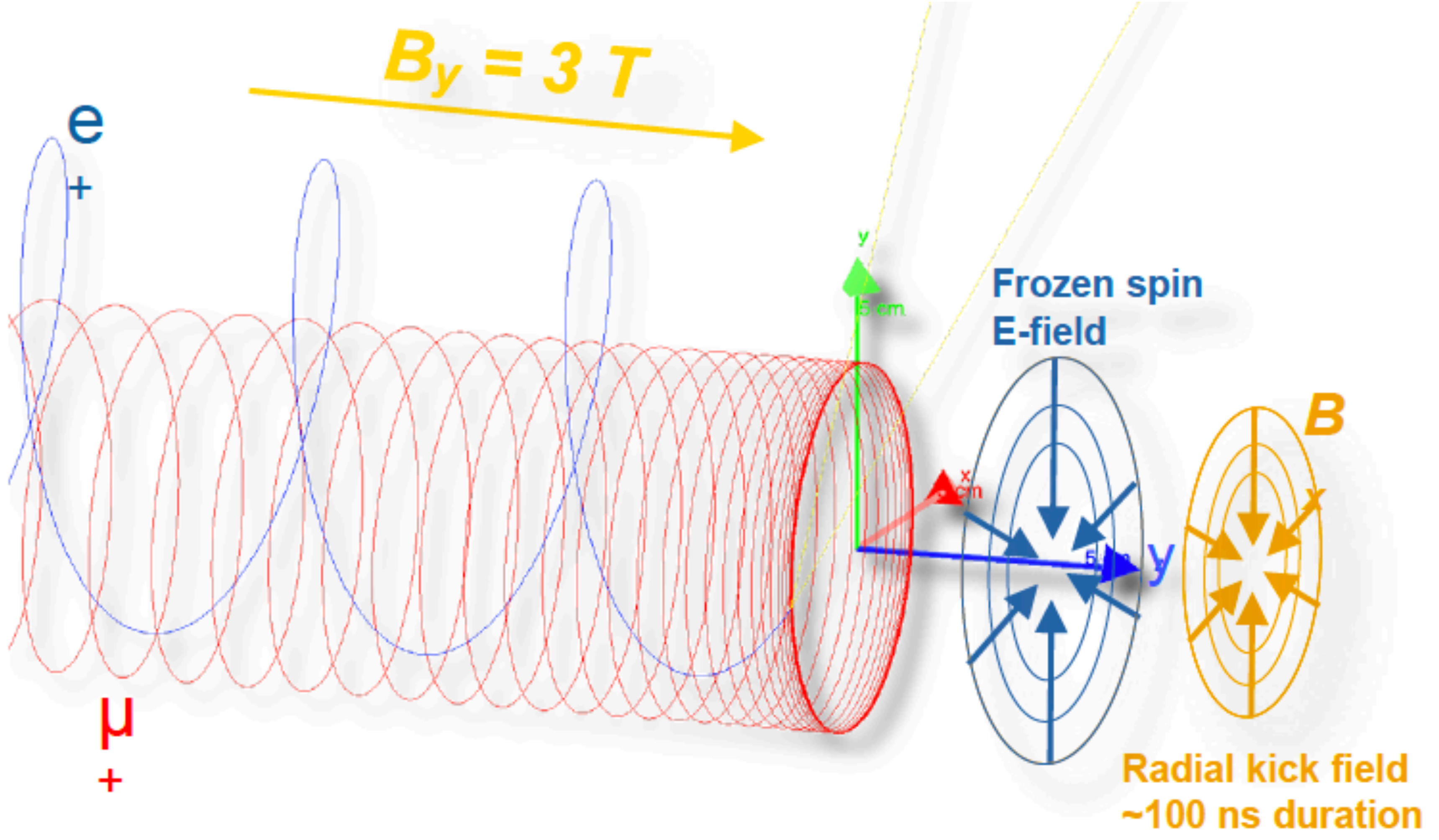
The slope gives the sensitivity of the measurement:

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

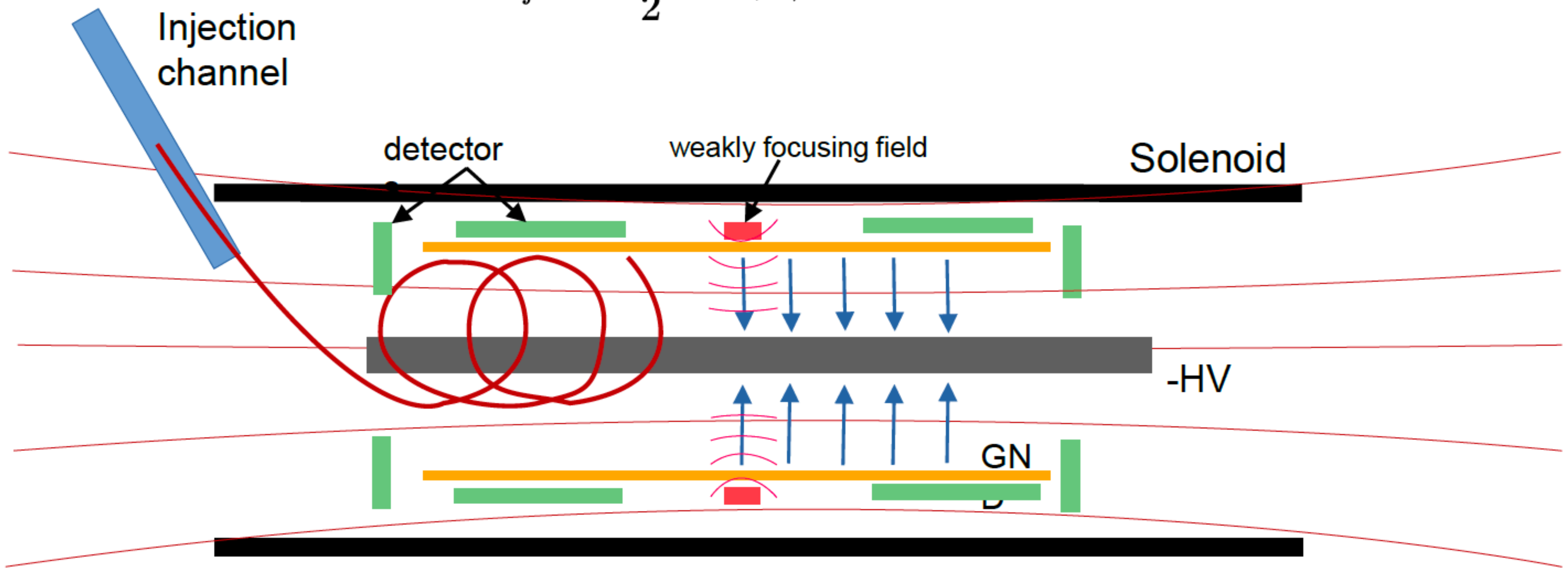
p := initial polarization
E_{f} := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_{μ} := lifetime of muon
α := mean decay asymmetry

The general experimental idea

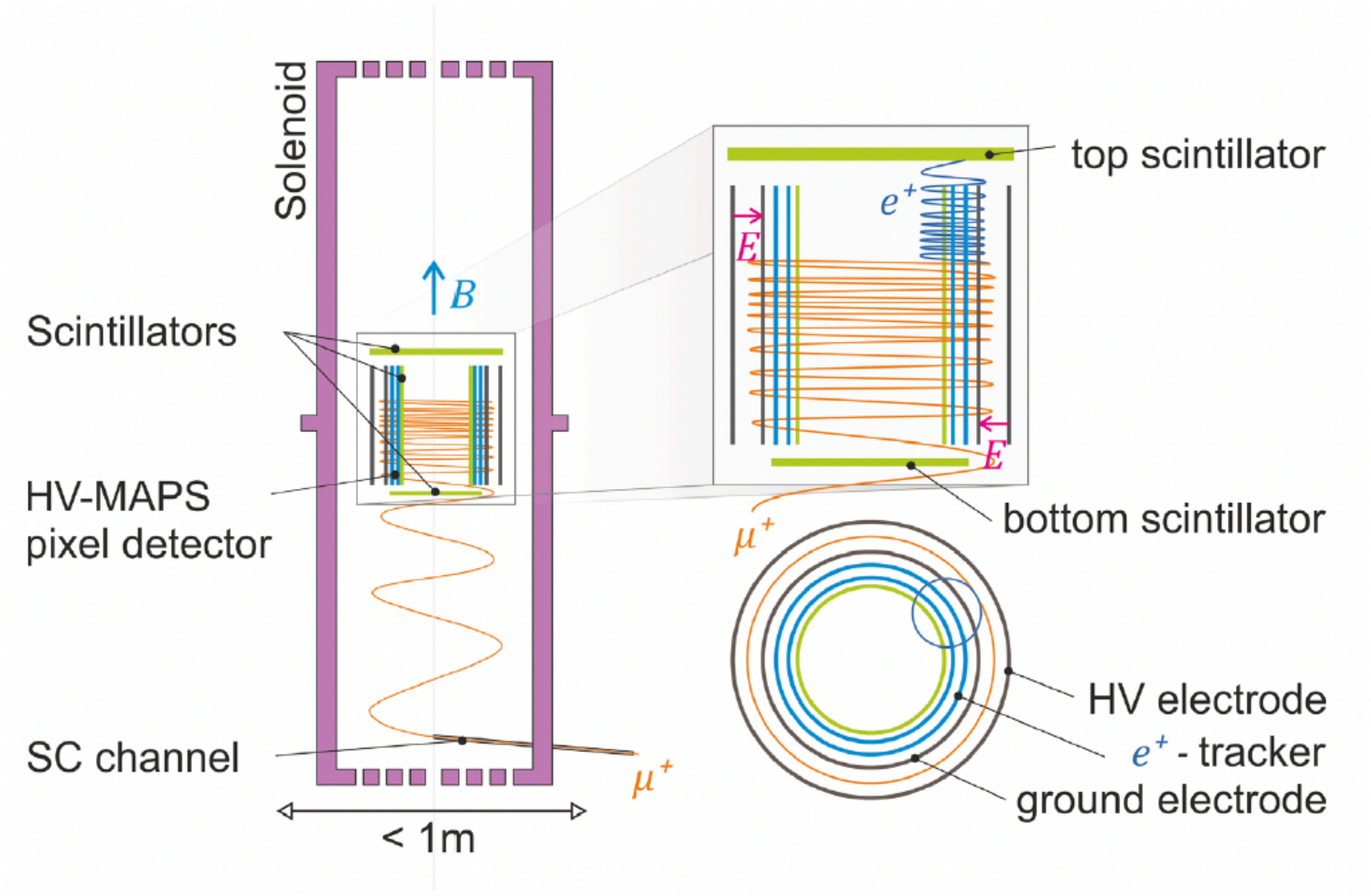
- Muons enter the uniform magnetic field
- A radial magnetic field pulse stops them within a weakly focusing field where they are stored
- Radial electric field ‘freezes’ the spin so that the precession due to the MDM is cancelled



$$E_f \approx \frac{g-2}{2} B c \beta \gamma^2$$



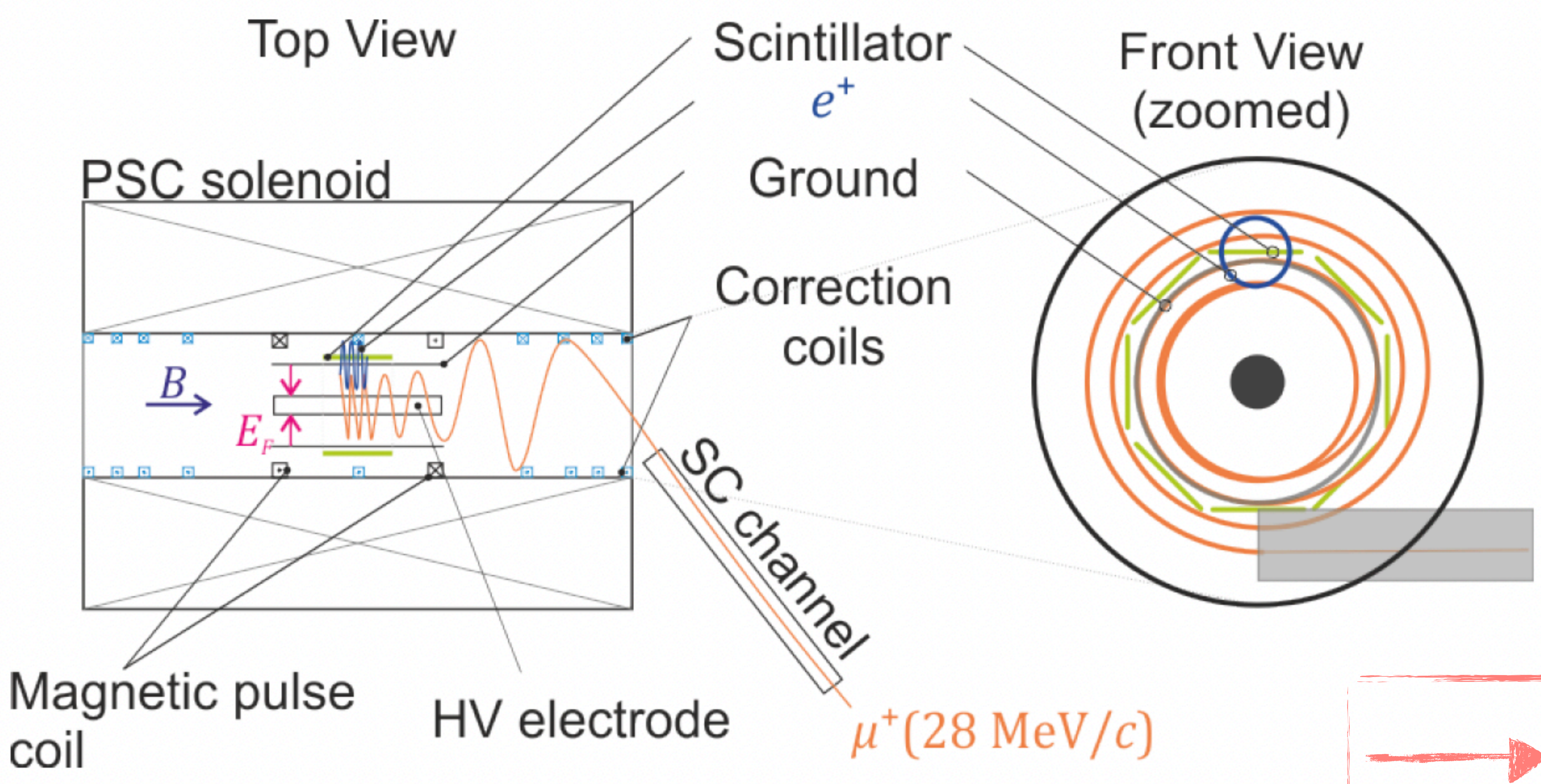
muEDM final at PSI: Frozen spin and longitudinal injection



p=125 MeV/c [muE1]

- μ^+ from Pion–decay → high polarization $p \approx 95\%$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of μ^+
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for e^+– tracking

muEDM Precursor at PSI: Proof-of-principle of the frozen spin technique



p=28 MeV/c [piE1]

Develop key technologies and design the final instrument

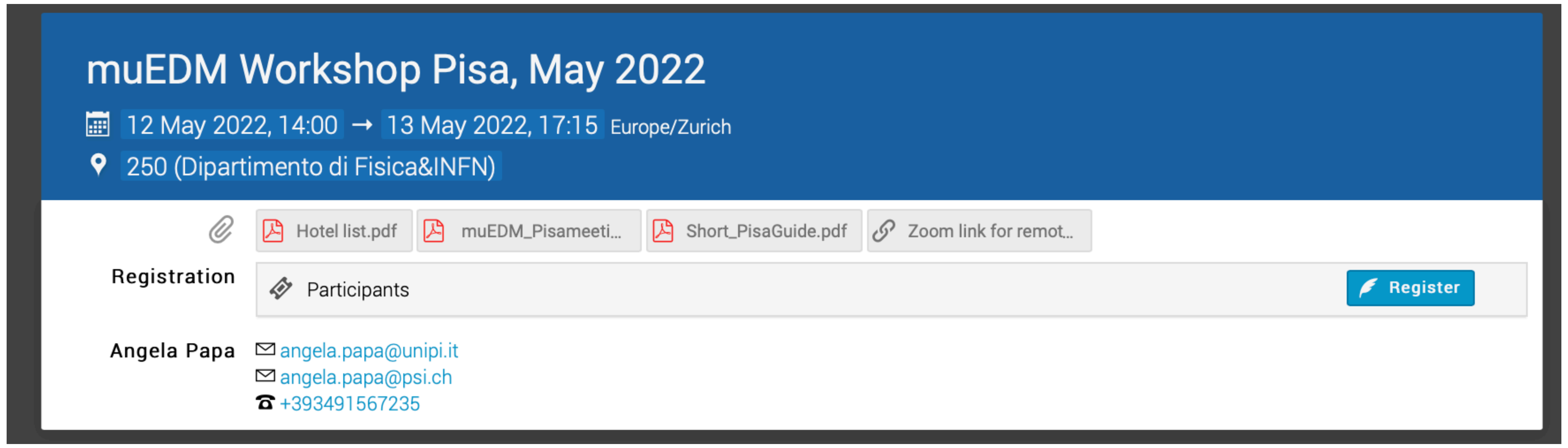
- Full MC model
- Full FEM model
- Analysis and DAQ
- Nested electrode system with a minimal material budget for the frozen-spin technique
- Pulsed magnetic field to kick muons on a stable orbit
- Injection channel made of a superconducting shield

Perform a first EDM measurement using existing infrastructure and solenoid at PSI

- Develop magnetic-field correction coils and field measurement device
- Develop dedicated positron and muon detectors
- Demonstrate injection
- Demonstrate for the first time electric-field tuning to frozen-spin condition
- First dedicated frozen-spin EDM measurement

First meeting in person in Pisa

- First discussion of tasks and potential interest
- Theoretical seminar (Paride Paradisi)
- Material available at the link: https://indico.psi.ch/event/12975/

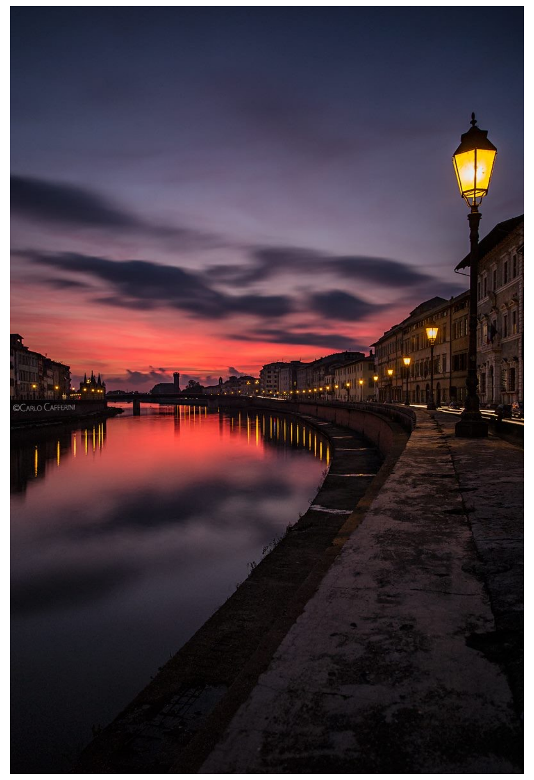


UNIVERSITÀ DI PISA

INFN

muEDM Workshop

Pisa - May 12-13 2022



PROGRAM

Sala seminario 250 - Building C - Physic Department & INFN sez. Pisa

1st Day

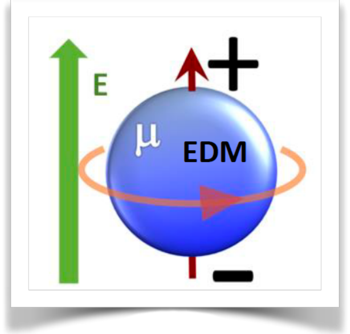
Arrivals	9:00 - 12:00
Collaboration meeting	14:00 - 16:30

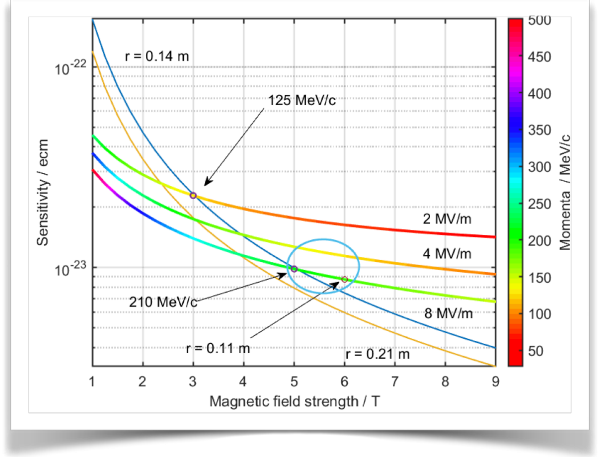
16:30 Seminar: EDMs, g-2 and cLFV interrelationship
Paride Paradisi, University of Padova & INFN

Social Dinner	19:00 - 22:00

2nd Day

Collaboration meeting	9:00 - 18:00



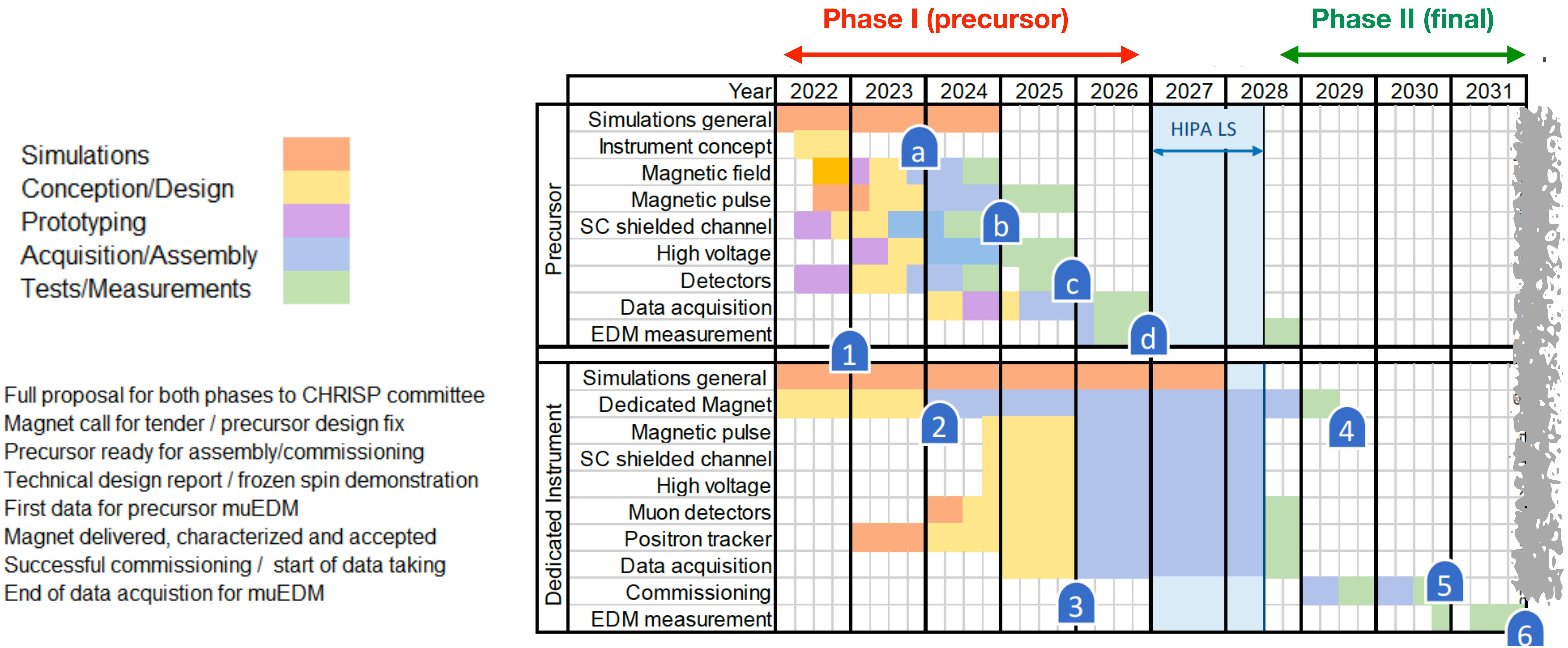


UNIVERSITY OF PISA AND ITALIAN NATIONAL NUCLEAR INSTITUTE

Foreign interested institutes

- (apart PSI, ETH Zurich, INFN):
  - University of Zurich, University of Geneve
  - University of Liverpool, University of London (UCL), University of Manchester, University of Sussex
  - Mainz, Mainz PRiSMA, Universitat Dortmund TU
  - Shanghai University, Tsung-Dao Lee Institute
  - Argonne National Laboratory, Brookhaven National laboratory

A tentative schedule

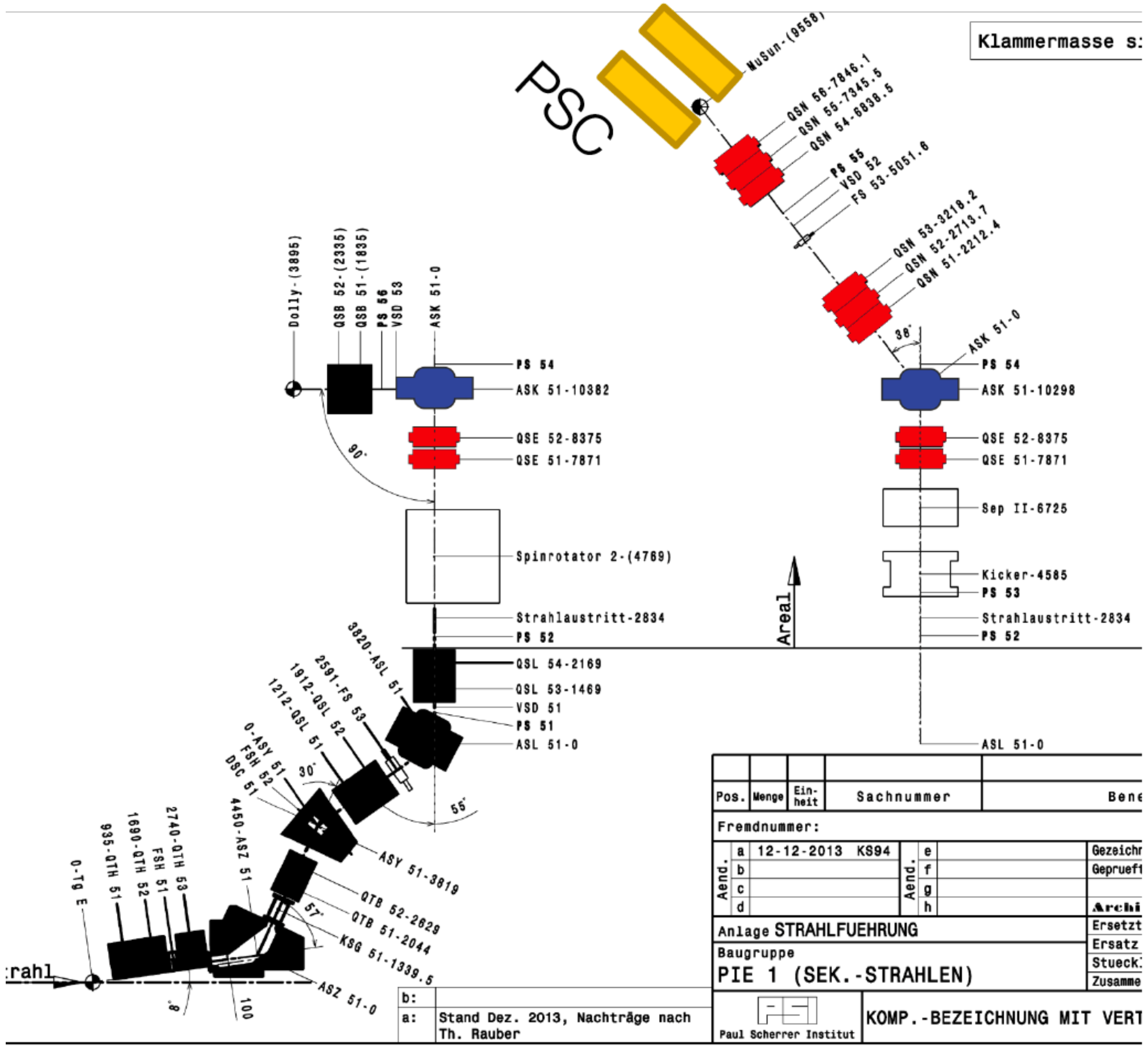


1	Full proposal for both phases to CHRISP committee
2/a	Magnet call for tender / precursor design fix
b	Precursor ready for assembly/commissioning
3/c	Technical design report / frozen spin demonstration
d	First data for precursor muEDM
4	Magnet delivered, characterized and accepted
5	Successful commissioning / start of data taking
6	End of data acquistion for muEDM

Key milestones of the precursor

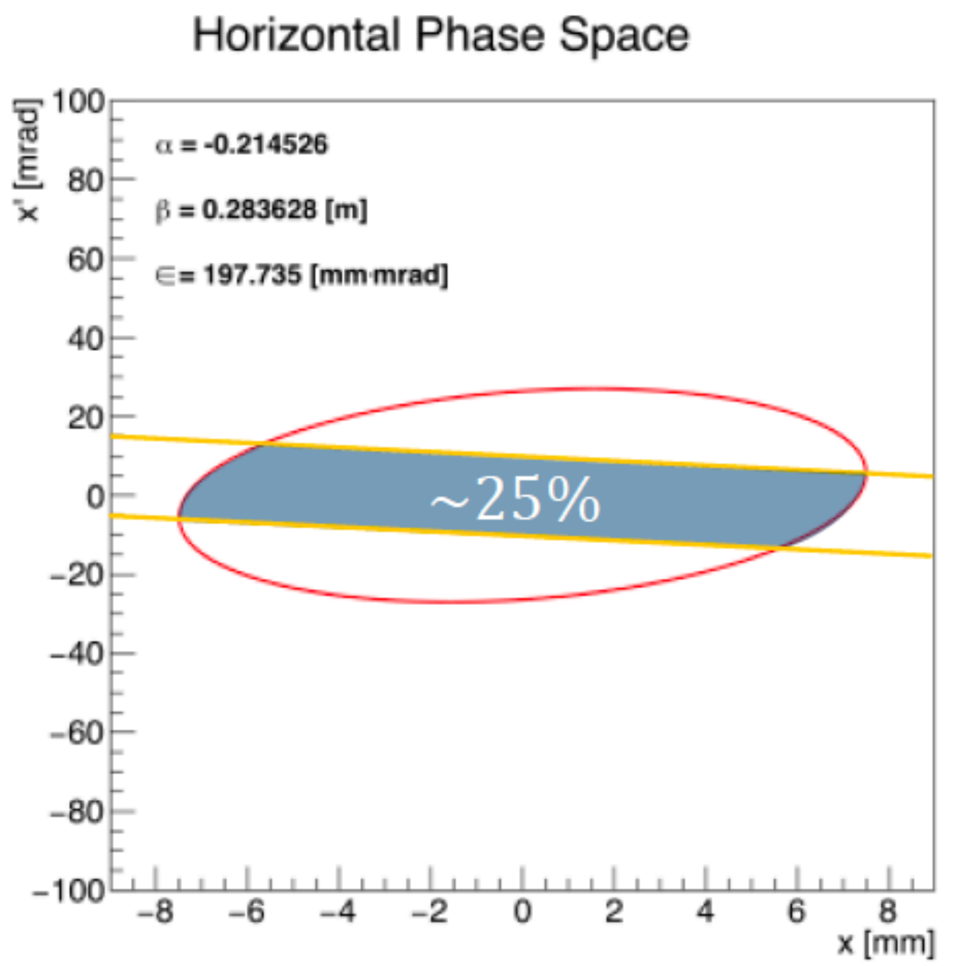
- Demonstrate the injection
- Demonstrate for the first time electric-field tuning to frozen spin condition
- And then…having detectors to prove it and eventually to perform the first measurement of muEDM with this technique
  - Plastic scintillators coupled to SiPM (Muon tagging, Top/bottom asymmetry and eventually positron tracking - at the first stage to keep the detector complexity at the minimum)
  - PTC feasibility study: muon tracking (to prove that the wanted muon tracks are the selected ones) [not excluded as positron tracker but other options could be more competitive]

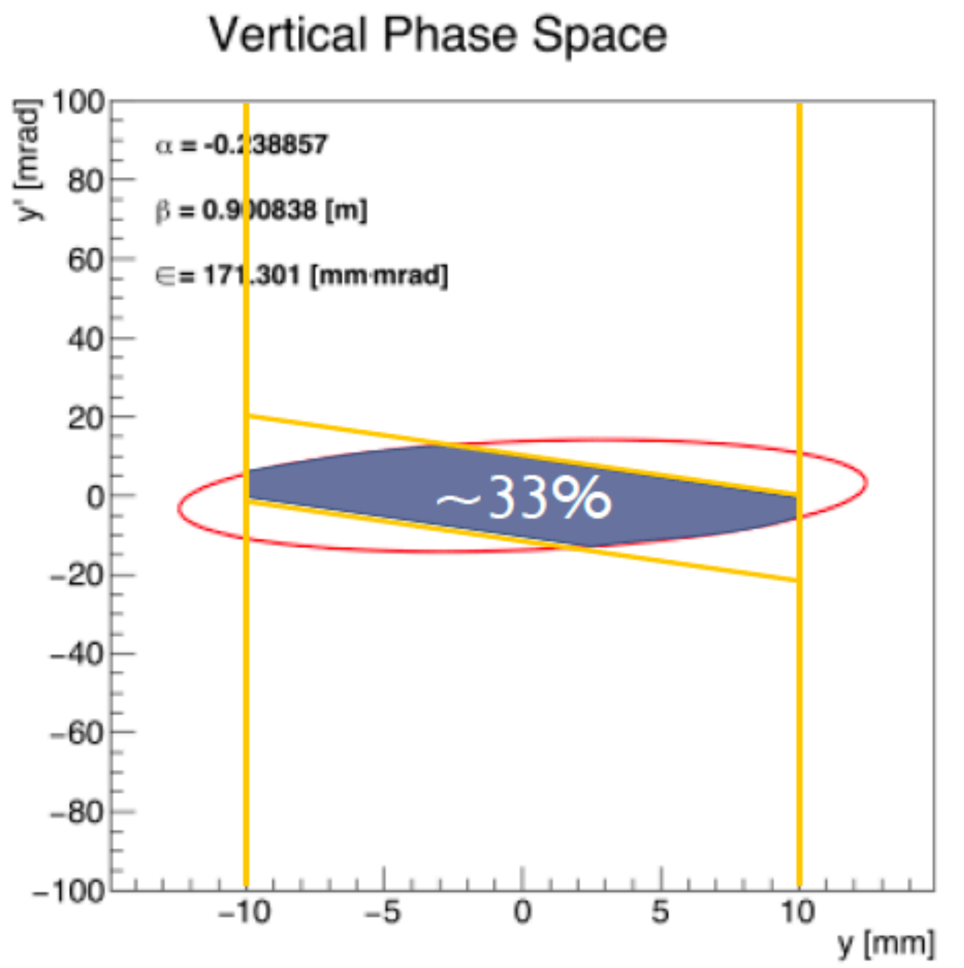
Beam-line at PSI for the precursor in piE1



- Surface muon beam at $28\ \mathrm{MeV}/c$
- Muon rate $\sim 3 \times 10^6$
- Test bed for development
- Demonstration of storage and detection of g-2/EDM, e.g. with PSC magnet $\emptyset = 200\,\mathrm{mm}$
  - the larger the bore the better for instrumentation

Beam measurements at PSI for the precursor in piE1



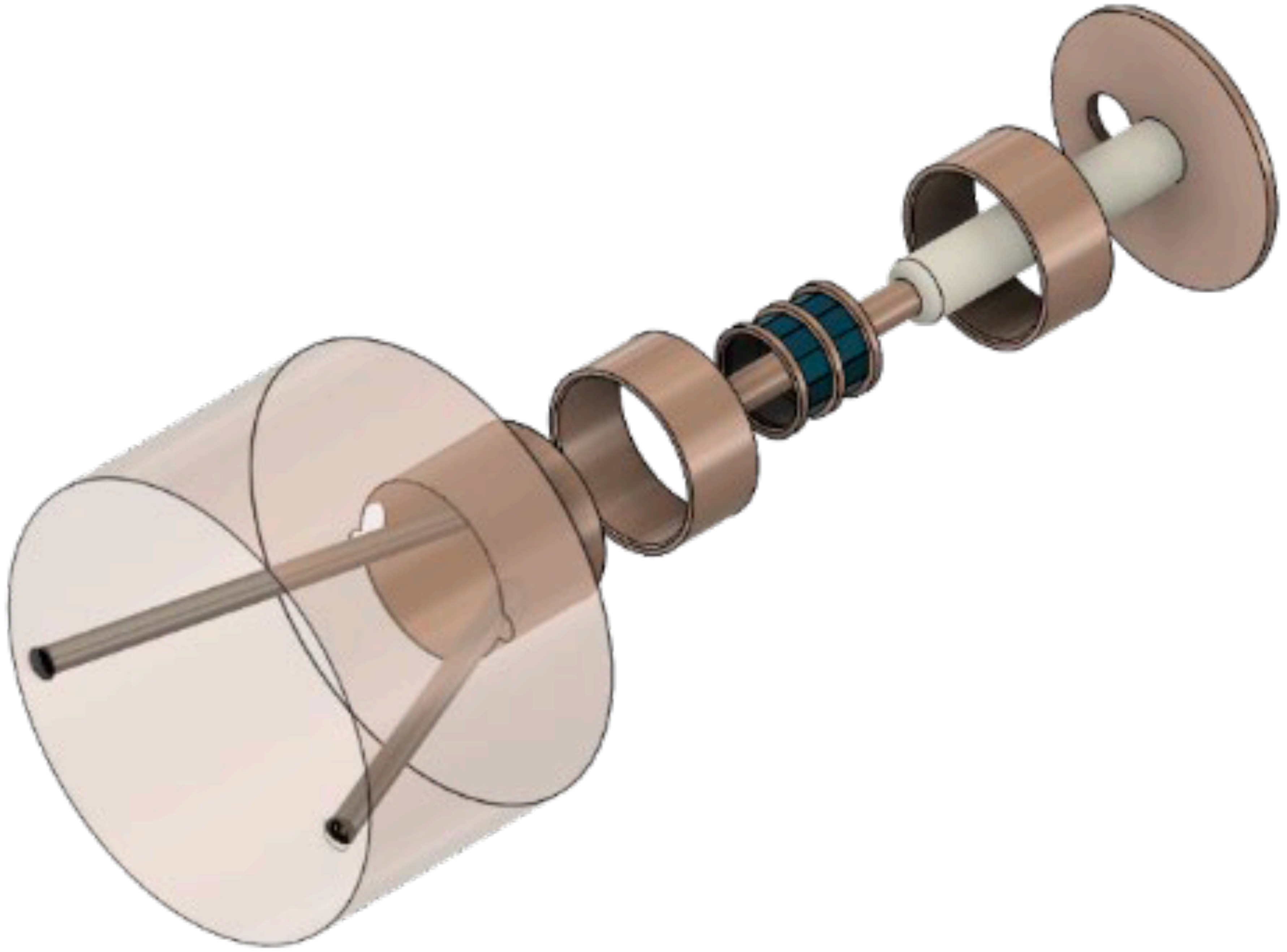


- Horizontal Emittance: **200 πmm mrad**
- Vertical Emittance: **270 π mm mrad**
- Beam rate about $2 \times 10^6\ \mathrm{s}^{-1}$
- Acceptance phase space:
  - High transmission through channel 6%
  - Injection efficiency about 2%
  - Expected e^+ detection rate 2kHz

- Moderate E field 3kV/cm

The “muEDM” magnet and the injection scheme

- The PSC magnet: Up to 5 T (3 T needed for muEDM)
- CAD view of the injection SC line, pulsed coils, HV electrodes, Grounds and support structure



Outlook

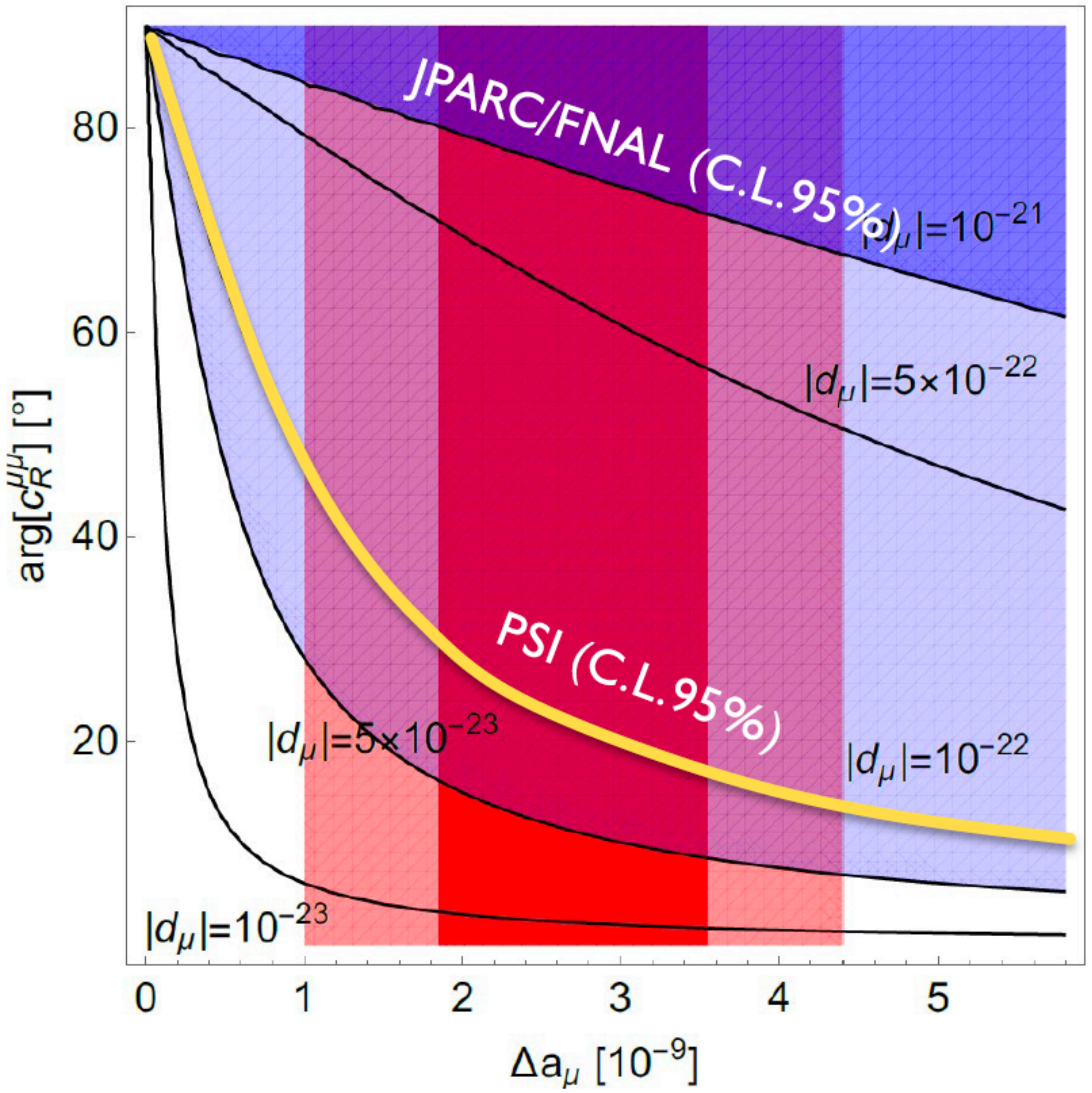
- A very attractive experiment with strong scientific motivations
- The main challenges: Beam related aspects and B and E fields, systematics and the analysis
- Quite stimulating to face with these new scientific tasks
- Large room for leading and shaping the experiment at different and complementary levels
- ERC (consolidator) just granted. It represents the base on which start to build the rest

...

Thank you for your attention!

Back-up

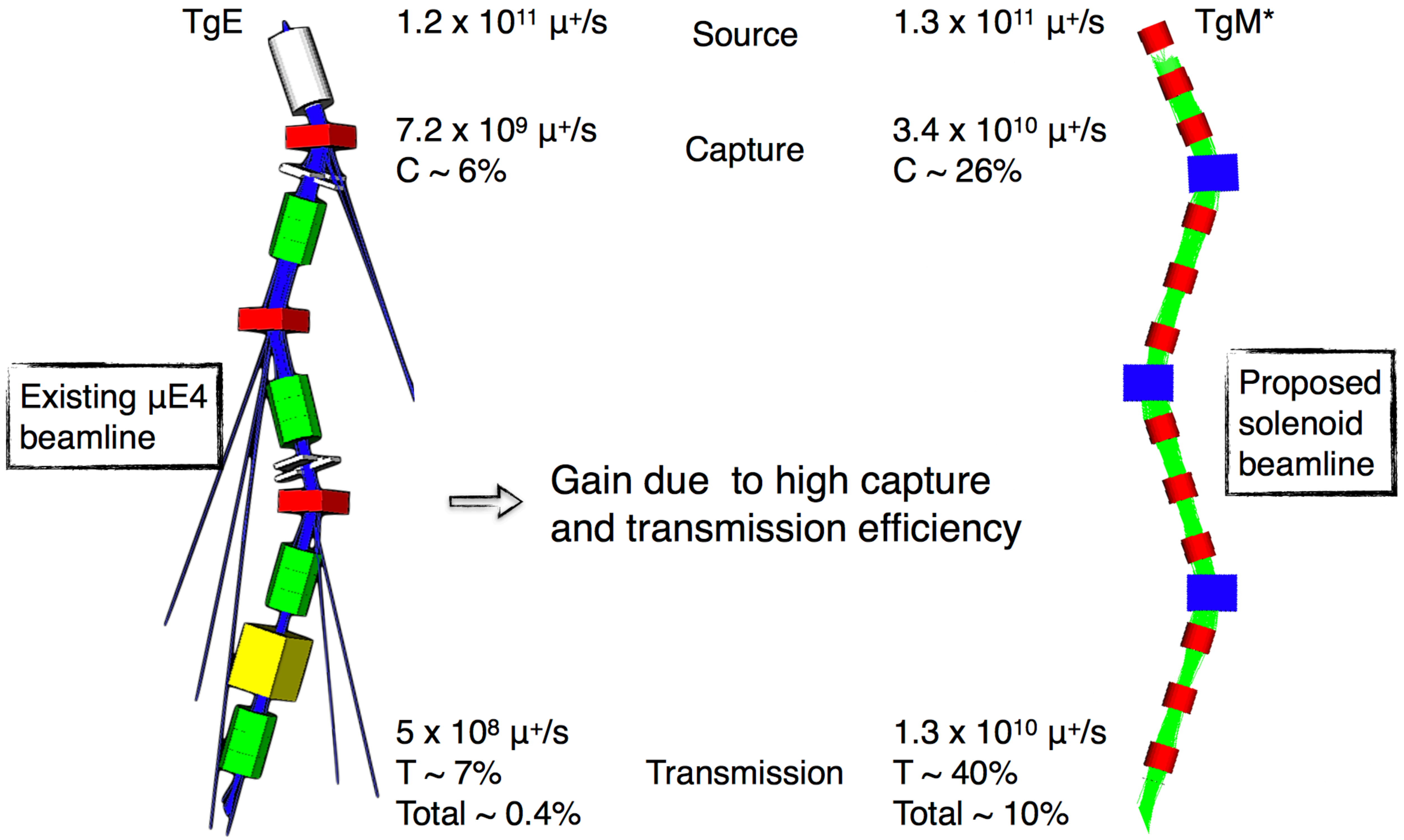
Sensitivity: Very preliminary



Gamma factor ($p_\mu = 125\mathrm{MeV}/c$)	γ	1.57
Initial polarization	P	0.95
Electric field ($B = 3T$)	E_f	2MV/m
e^+ detection rate 25%		60kHz
Mean decay asymmetry	α	0.3
Detections (200days)	N	10^{12}
$\sigma = \hbar\gamma a_\mu/(2PE_\mathrm{f}\sqrt{N}\tau_\mu\alpha)$	$<$	6×10^{-23} ecm

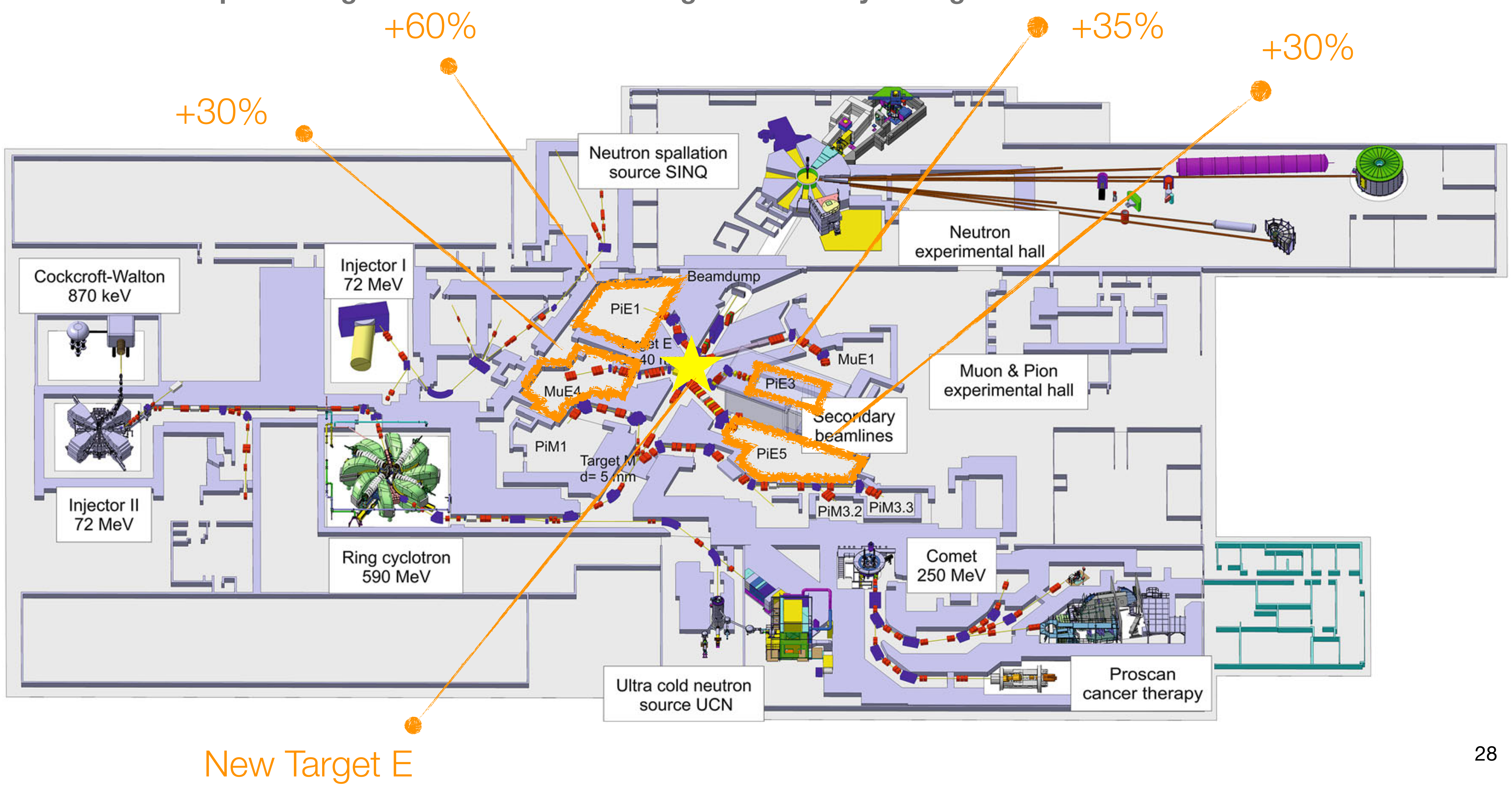
DC muon beams. Future prospects: HiMB

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2027)**
- **Key elements: Slanted Target and optimised beam line** (higher capture efficiency and large space acceptance transport channel)



Slanted target: First test on 2019 and since then in operation

- Expect ~30-60 % enhancement
- Measurements successfully done in different experimental areas in fall 2019
- **Increased muon yield CONFIRMED!**
- To be seen: **impact of higher thermal stress on long term stability of target wheel**

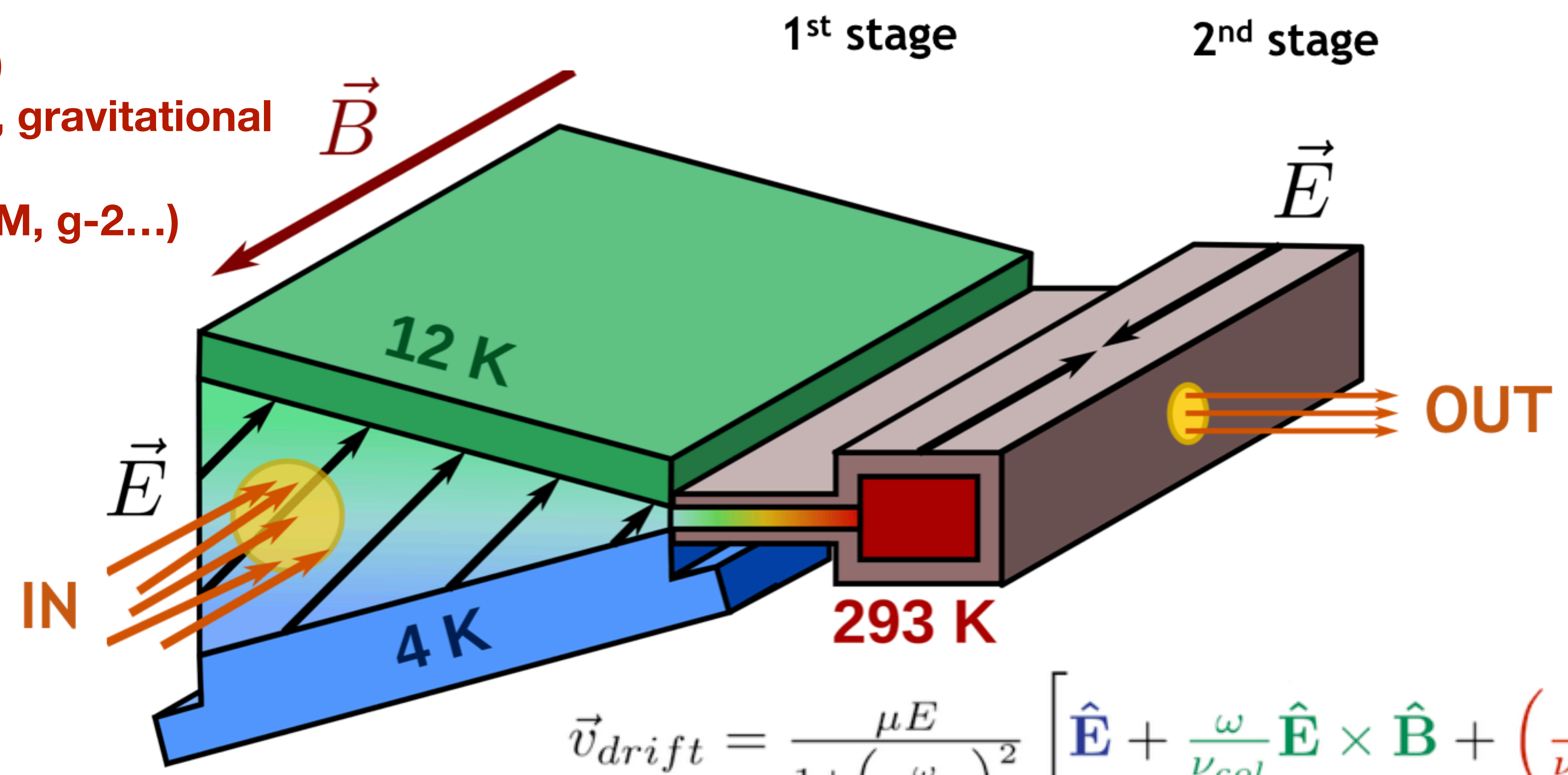


D. Taqqu, PRL 97 (2006) 194801
Y. Bao et al., PRL 112 (2014) 224801
I. Belosevic et al., EPJ C 79 (2019) 430

The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-3}**
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum

µSR (solid state physics)
muonium (spectroscopy, gravitational interaction...)
muon experiments (µEDM, g-2…)



$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

Few numbers

- Precision achieved in the studies of magnetic dipole moments

$$\Delta\left(a_e^{\rm SM} - a_e^{\rm exp}\right) \simeq 10^{-12}$$
$$\Delta\left(a_\mu^{\rm SM} - a_\mu^{\rm exp}\right) \simeq 10^{-9}$$

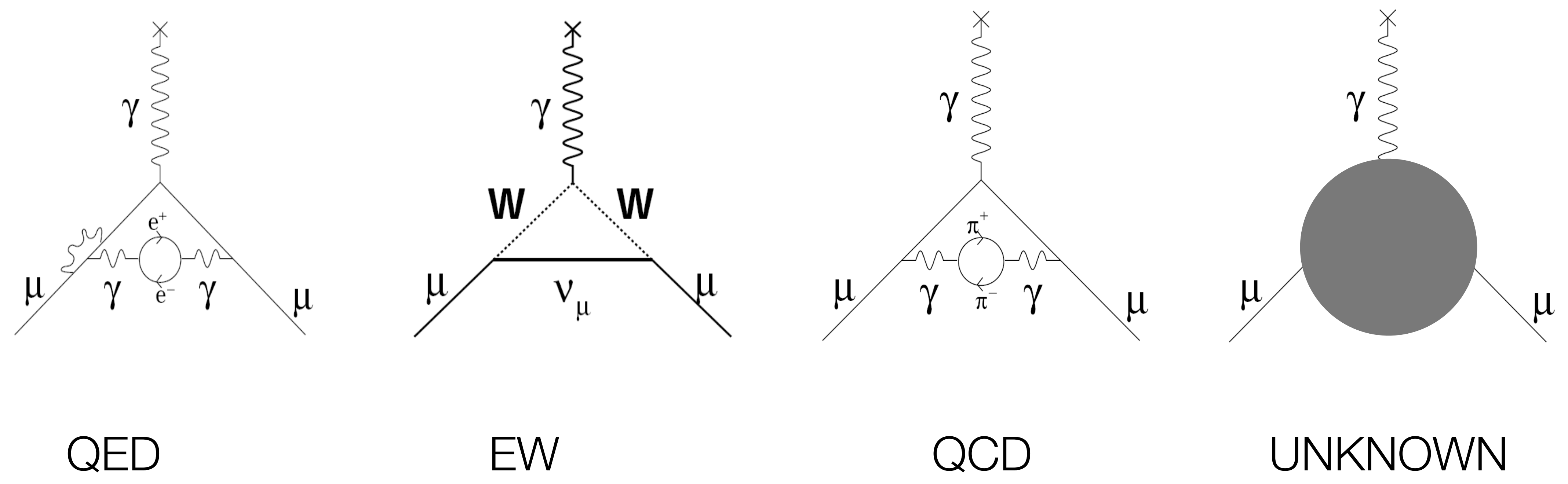
- Sensitivity to new physics scales like the lepton mass squared

$$a_f^{\rm NP} \sim \frac{m_f^2}{\Lambda^2}$$

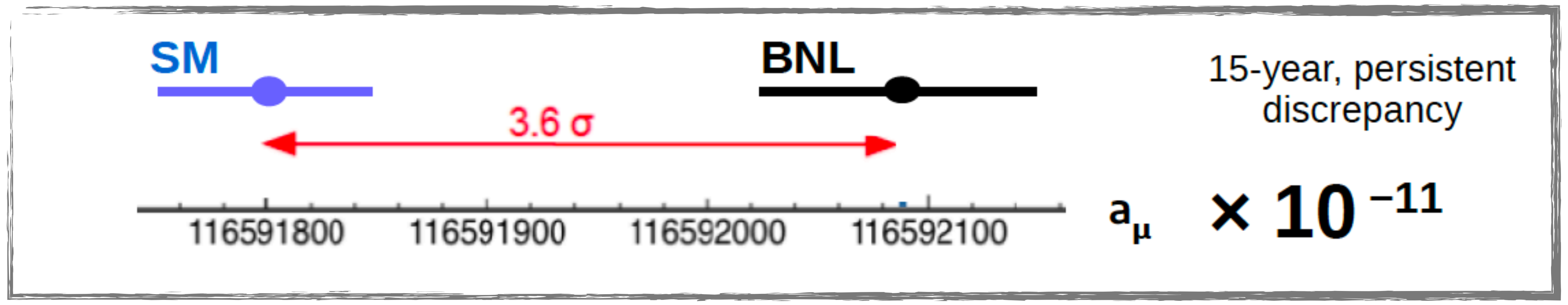
- Muon is a more sensitive probe (but electron is becoming relevant…)

$$\frac{\Lambda_\mu}{\Lambda_e} \sim \frac{m_\mu}{m_e}\sqrt{\frac{\Delta a_e}{\Delta a_\mu}} \sim 6$$

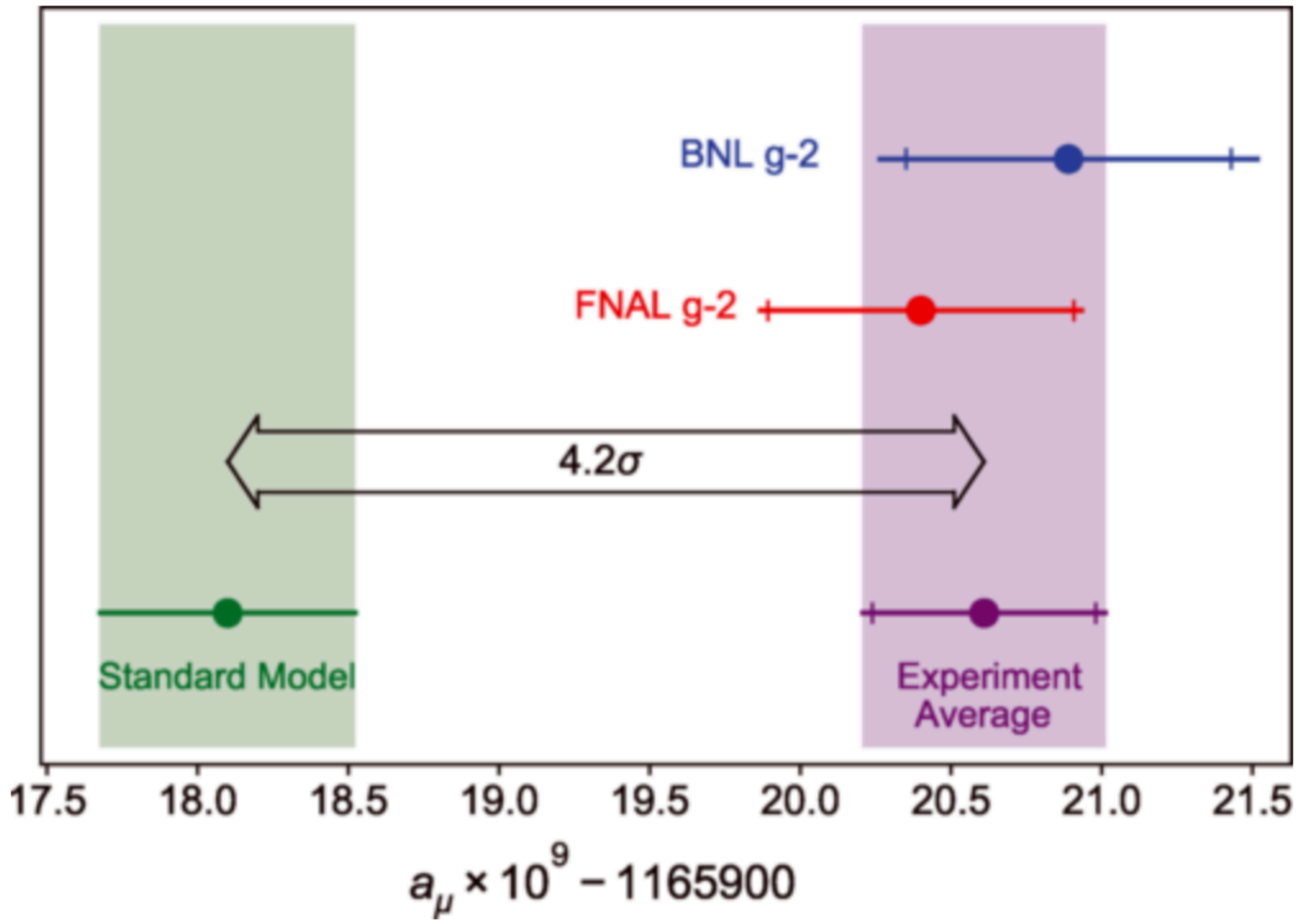
A glimpse: g-2 experiments and EDM



$$\mu = (1 + a_\mu)\frac{e\hbar}{2m} \qquad a_\mu = \frac{g_\mu - 2}{2}$$



- Dirac's relativistic theory predicted muon magnetic moment “g” = 2
- Experiment suggested that g-factor differs from the expected value of 2
- Standard Model prediction: a(SM) = a(QED) + a(Had) + a (Weak) + **a (NP)**
- BNL E821 result: 3.3σ deviation from SM prediction
- FNAL First Result: **April 2021 [using RUN1 with statistics similar to BNL statistics]**
- **RUN1-3 (already collected): ~ 8x BNL statistics. Aiming at ~ 20x BNL statistics**



Reminder

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R\sigma_{\mu\nu}A_{\ell\ell'}\ell'_L + \bar{\ell}'_L\sigma_{\mu\nu}A^\star_{\ell\ell'}\ell_R\right)F^{\mu\nu} \qquad \ell,\ell' = e,\mu,\tau\,,$$

  - **Branching ratios of $\ell \to \ell'\gamma$**

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

  - **Δa_ℓ and leptonic EDMs**

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell})\,.$$

  - **"Naive scaling":**

$$\Delta a_\ell/\Delta a_{\ell'} = m_\ell^2/m_{\ell'}^2\,, \qquad d_\ell/d_{\ell'} = m_\ell/m_{\ell'}\,.$$

Back-up

- **LFV** operators **@ dim-6**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2_{\rm LFV}} \mathcal{O}^{\rm dim-6} + \ldots .$$

$$\mathcal{O}^{\rm dim-6} \ni \;\; \bar{\mu}_R \, \sigma^{\mu\nu} \, H \, e_L \, F_{\mu\nu} \, , \;\; (\bar{\mu}_L \gamma^\mu e_L) \, (\bar{f}_L \gamma^\mu f_L) \;, \;\; (\bar{\mu}_R e_L) \, (\bar{f}_R f_L) \;, \; f = e, u, d$$

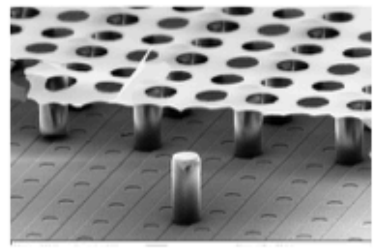
- $\ell \to \ell' \gamma$ probe ONLY the dipole-operator (at tree level)
- $\ell_i \to \ell_j \bar{\ell}_k \ell_k$ and $\mu \to e$ in Nuclei probe dipole and 4-fermion operators
- When the dipole-operator is dominant:

$$\mathrm{BR}(\ell_i \to \ell_j \ell_k \bar{\ell}_k) \approx \alpha \times \mathrm{BR}(\ell_i \to \ell_j \gamma)$$
$$\mathrm{CR}(\mu \to e \text{ in N}) \approx \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

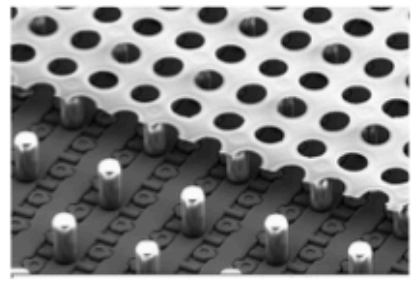
$$\frac{\mathrm{BR}(\mu \to 3e)}{3 \times 10^{-15}} \approx \frac{\mathrm{BR}(\mu \to e\gamma)}{5 \times 10^{-13}} \approx \frac{\mathrm{CR}(\mu \to e \text{ in N})}{3 \times 10^{-15}}$$

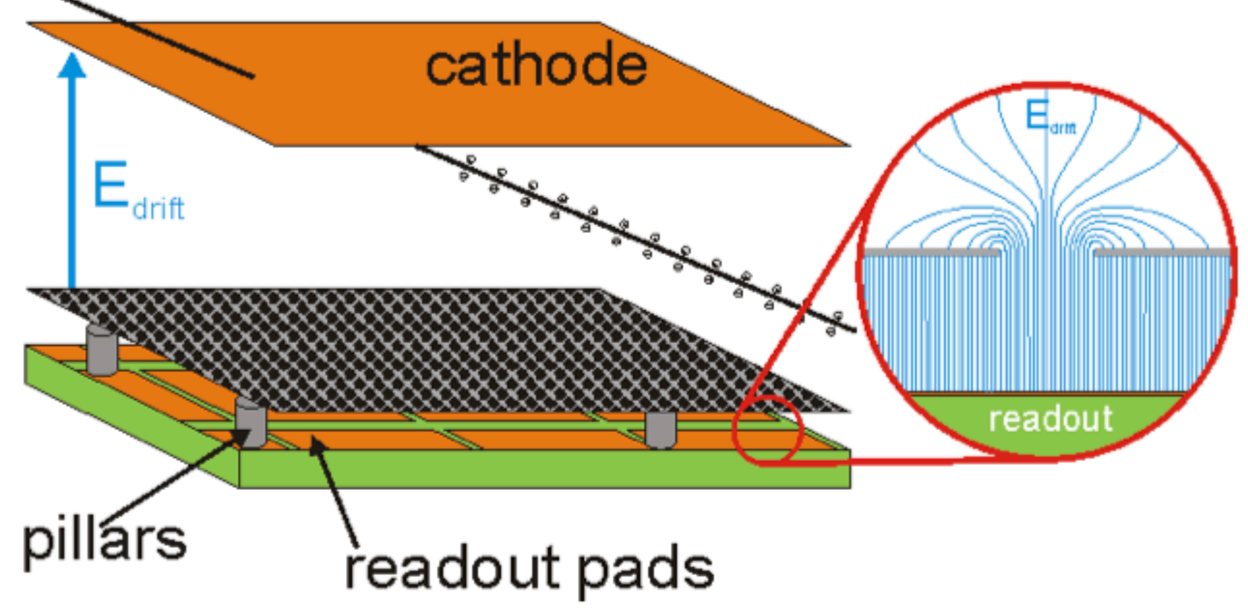
- **Ratios like** $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ **probe the NP flavor structure**
- **Ratios like** $Br(\mu \to e\gamma)/Br(\mu \to eee)$ **probe the NP operator at work**

GridPix



Improving Micromegas: GridPix





Could the spatial resolution of single electrons be improved?

Ar:CH_4 90:10 → D_T = 208 µm/√cm

→ σ = 24 µm

Ar:iButane 95:5 → D_T = 211 µm/√cm

→ σ = 24 µm

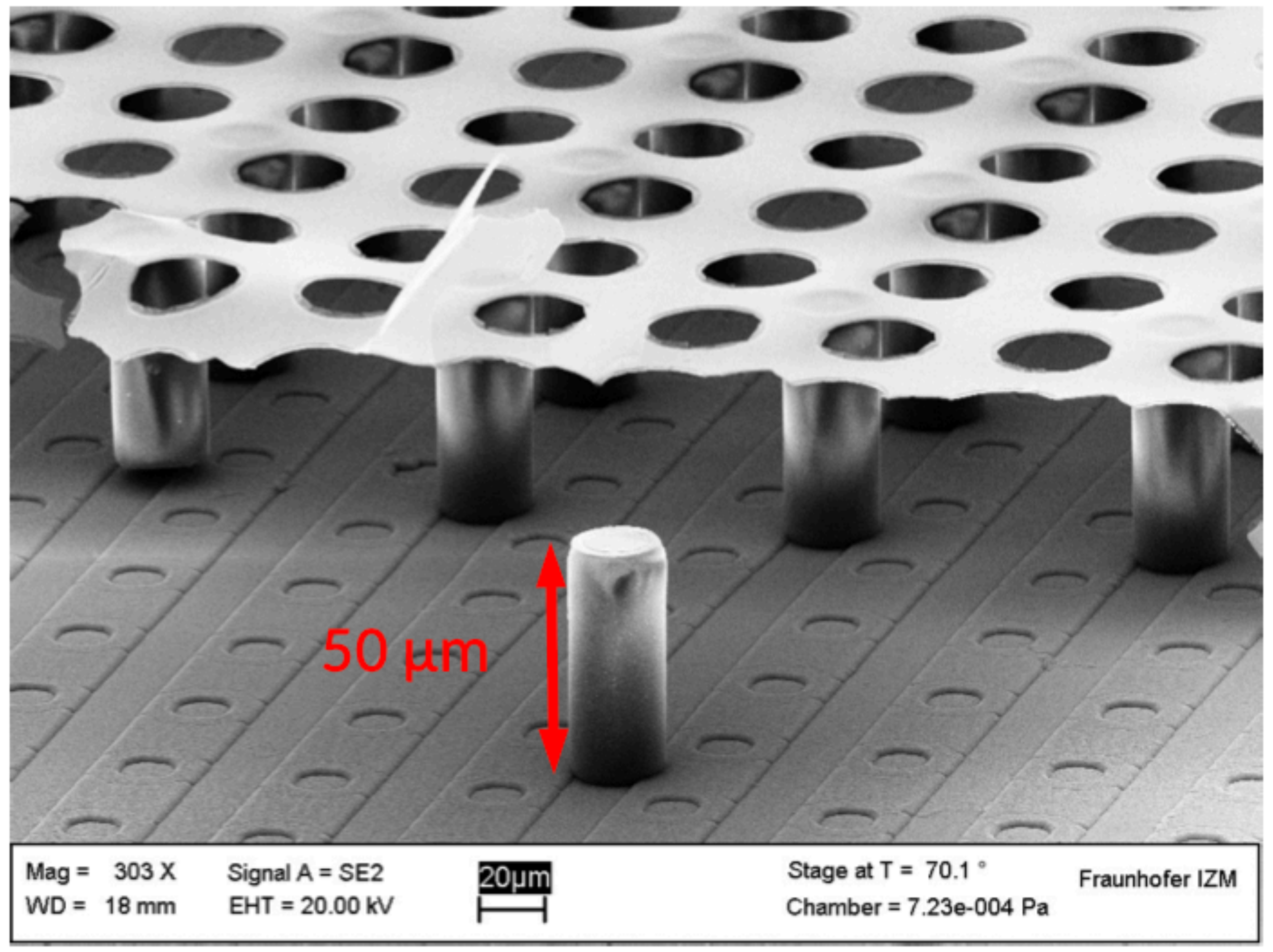
Smaller pads/pixels could result in better resolution!

At Nikhef the GridPix was invented.

Standard charge collection:

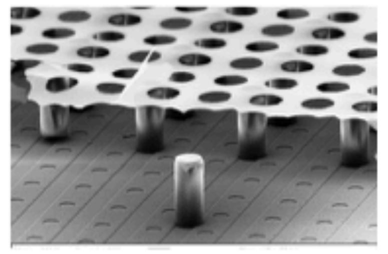
- Pads of several mm²
- Long strips (l~10 cm, pitch ~200 µm)

Instead: Bump bond pads are used as charge collection pads.

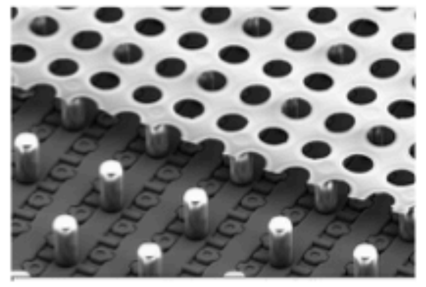


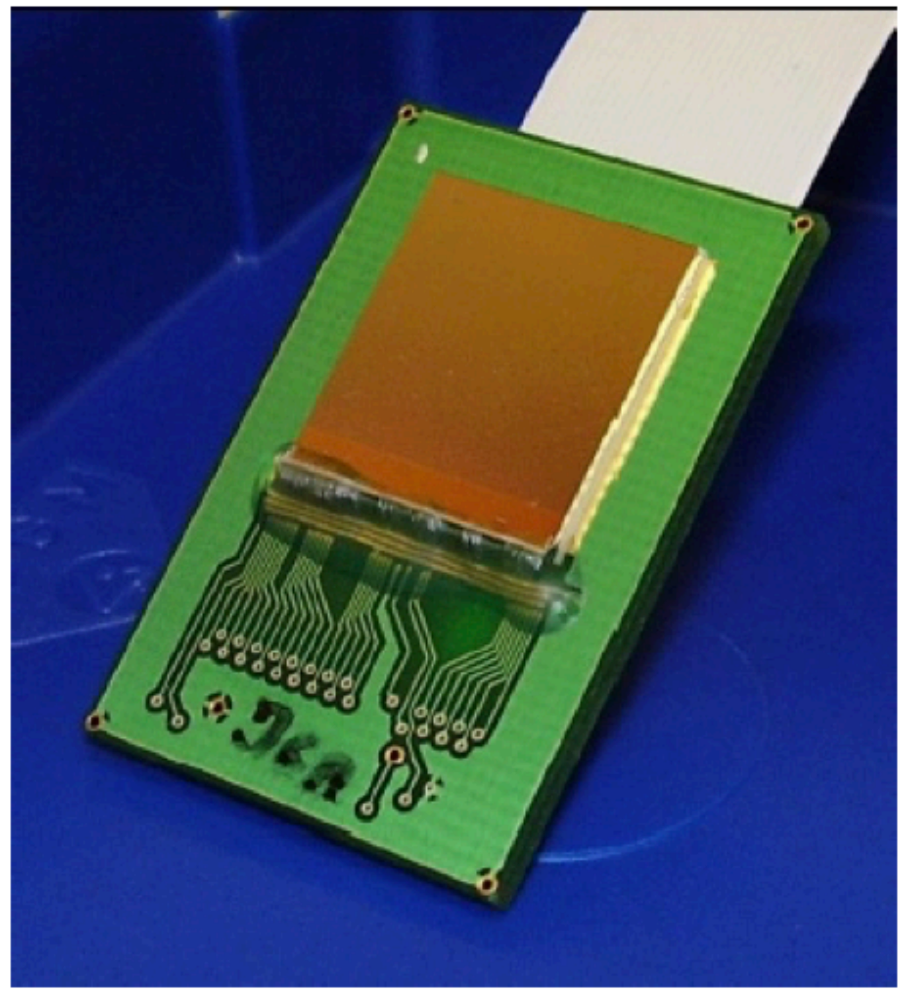
universitätbonn

GridPix



Timepix





Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 µm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e⁻

Limitations: no multi-hit capability, charge and time measurement not possible for one pixel. Each pixel can be set to one of these modes: TOT = time over threshold (charge)
Time between hit and shutter end.