Future projects at PSI

Workshop on status and perspectives of physics at high intensity

Frascati 10-11-2022

Paolo Walter Cattaneo
INFN Pavia

A next-generation rare pion decay experiment

W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12] A. Di Canto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17] M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16] J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5] T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15] D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13] A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

[1] *Santa Cruz Institute for Particle Physics (SCIPP), University of California Santa Cruz, 1156 High street, Santa Cruz (CA) 95064 USA*
[2] *Department of Physics, University of Washington, Box 351560, Seattle, Washington 98195 USA*
[3] *Enrico Fermi Institute and Department of Physics, University of Chicago, 5720 South Ellis Avenue, Chicago, IL 60637 USA*
[4] *Department of Physics & Astronomy, University of British Columbia 6224 Agricultural Road, Vancouver V6T 1Z1 Canada*
[5] *TRIUMF, 4004 Wesbrook Mall, Vancouver V6T 2A3 Canada*
[6] *Paul Scherrer Institute, 5232 Villigen PSI Switzerland*
[7] *Department of Engineering Physics, Tsinghua University, 30 Shuangqing Road, Haidian District, Beijing, 100084 P. R. China*
[8] *Institute for Nuclear Theory, University of Washington, Seattle WA 98195-1550 USA*
[9] *Argonne National Laboratory, High Energy Physics Division, 9700 S Cass Ave, Lemont, IL 60439 USA*
[10] *Physik-Institut University of Zurich Winterthurerstrasse 190 CH-8057 Zurich Switzerland*
[11] *Division of Theoretical Physics, CERN, Espl. des Particules 1, 1211 Meyrin Switzerland*
[12] *Tecnológico de Monterrey, School of Engineering and Sciences, Blvd. Pedro Infante 3773 Pte, Culiacan 80100 Mexico*
[13] *Physics Department, Brookhaven National Laboratory, Upton, NY, 11973 USA*
[14] *PRISMA⁺ Cluster of Excellence and Johannes Gutenberg Universität Mainz, Institut für Kernphysik, J.-J.-Becher-Weg 45, 55128 Mainz Germany*
[15] *Fermi National Accelerator Laboratory (FNAL), P.O. Box 500, Batavia IL 60510-5011 USA*
[16] *Department of Physics, Cornell University, 109 Clark Hall, Ithaca, New York 14853 USA*
[17] *Department of Physics, University of Virginia, P.O. Box 400714, 382 McCormick Road, Charlottesville, VA 22904-4714 USA*
[18] *ETH Zurich, Main building, Rämistrasse 101, 8092 Zurich Switzerland*
[19] *Department of Physics and Astronomy, University of Kentucky, 505 Rose Street Lexington, Kentucky 40506-0055 USA*
[20] *Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland*
[21] *KEK, High Energy Accelerator Research Organization, 1-1, Oho, Tsukuba-city, Ibaraki 305-0801 Japan*
[22] *International Center for Elementary Particle Physics (ICEPP), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan*
[23] *Department of Chemistry – TRIGA site, Johannes Gutenberg University Mainz, Fritz-Strassmann-Weg 2, 55128 Mainz Germany*
[1] *C. N. Yang Institute for Theoretical Physics and Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794 USA*
[25] *Department of Physics and Astronomy, Elliott Building, University of Victoria, Victoria, BC V8P 5C2 Canada*
[26] *Instrumentation Division, Brookhaven National Laboratory, Upton, NY, 11973 USA*

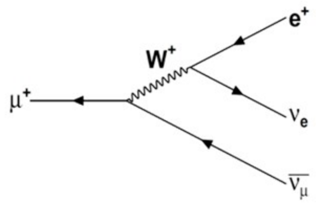
arxiv:2203.0198v1 [hep-ex] 8 mar 2022
arxiv:2203.0550v1 [hep-ex] 10 Mar 2022

A *Growing* Collaboration: New members very welcome !!

Lepton Flavor Universality is a simple concept:

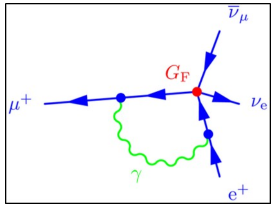
The weak interaction bare gauge couplings among leptons are the same e / μ / τ

- The weak-interaction "strength" is associated with the Fermi Constant, G_F
- Muon decay provides the most precise measurement
  - Technically it determines G_μ, which is usually just called G_F … because we believe in LFU !



G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}(1+q)$$



PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)

Questioning the validity of what others took to be true…

PHYSICAL REVIEW D, VOLUME 60, 093006

Fermi constants and "new physics"

William J. Marciano

Brookhaven National Laboratory, Upton, New York 11973

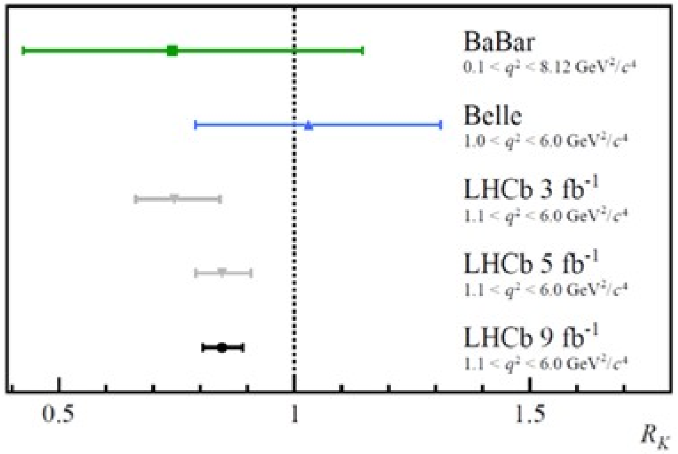
(Received 25 March 1999; published 7 October 1999)

Status now? Strong hints of problems with various *B* decay channels and leptons*

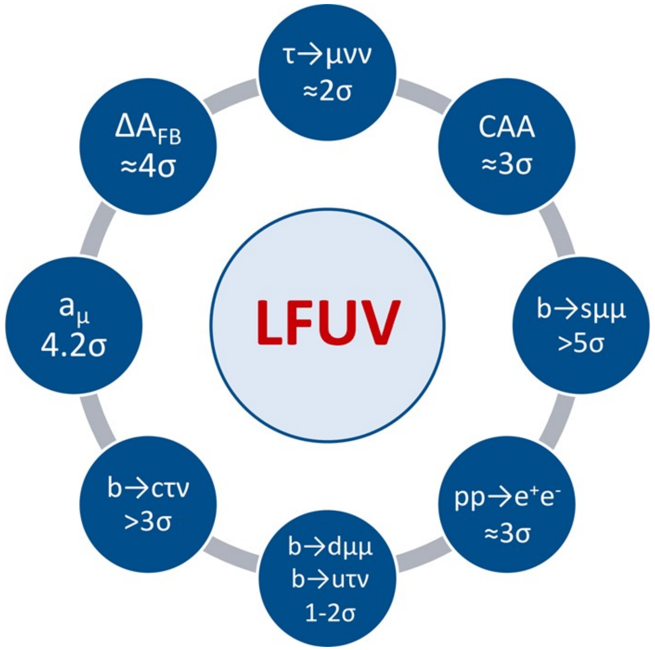
$B \to D^{(*)}\tau\nu$ / $B \to D^{(*)}\mu\nu$; charged currents

$B \to K^{(*)}\mu\mu$ / $B \to K^{(*)} ee$; neutral currents

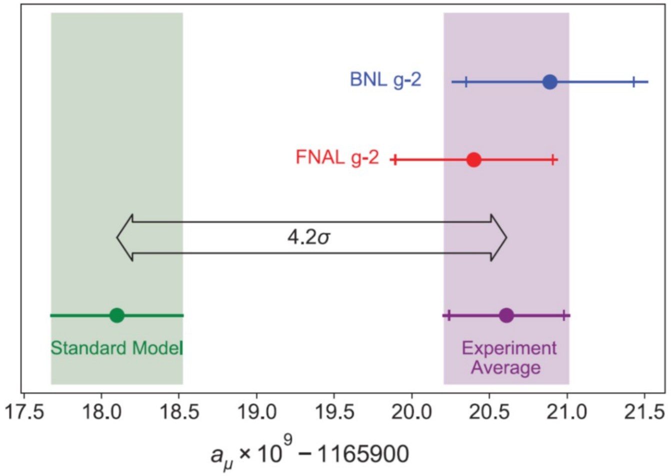
Also, “lots” of anomalies are associated with flavor measurements



arXiv:2204.12175 [hep-ph]



O(10%) deviations from universality !



Physics Case 1: Test LFUV at precision of theory

- Lepton Flavor Universality test in $R_{e/\mu}^{theory} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$

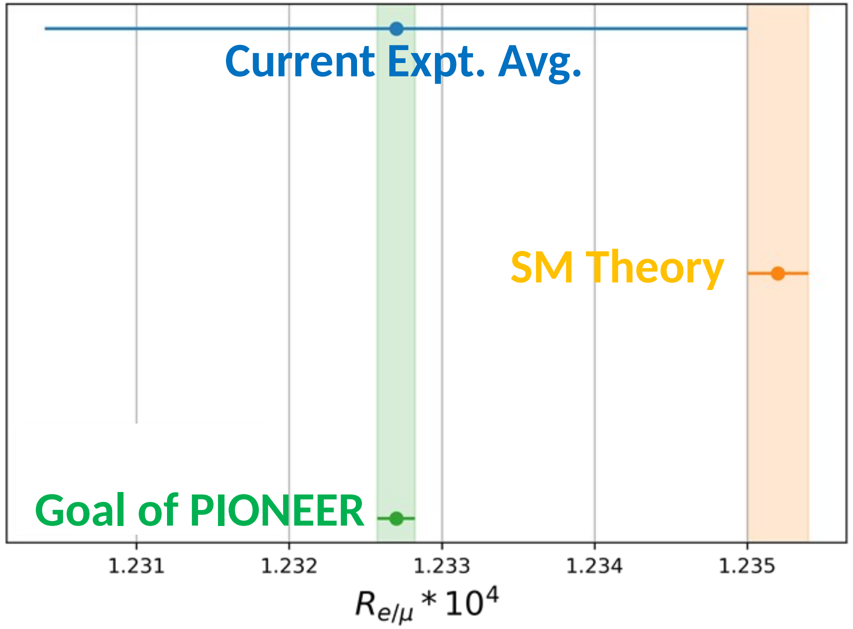
$$R_{e/\mu}(\text{SM}) = 1.23524(015) \times 10^{-4}$$

$$R_{e/\mu}(\text{Exp}) = 1.23270(230) \times 10^{-4}$$

15 x worse than theory

$$\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009 \ \ (\pm 0.09\%)$$

(dominated by PIENU expt.)



This just demands to be tested better! A clean generic way to look for new physics. Theory vs Experiment in high precision test.

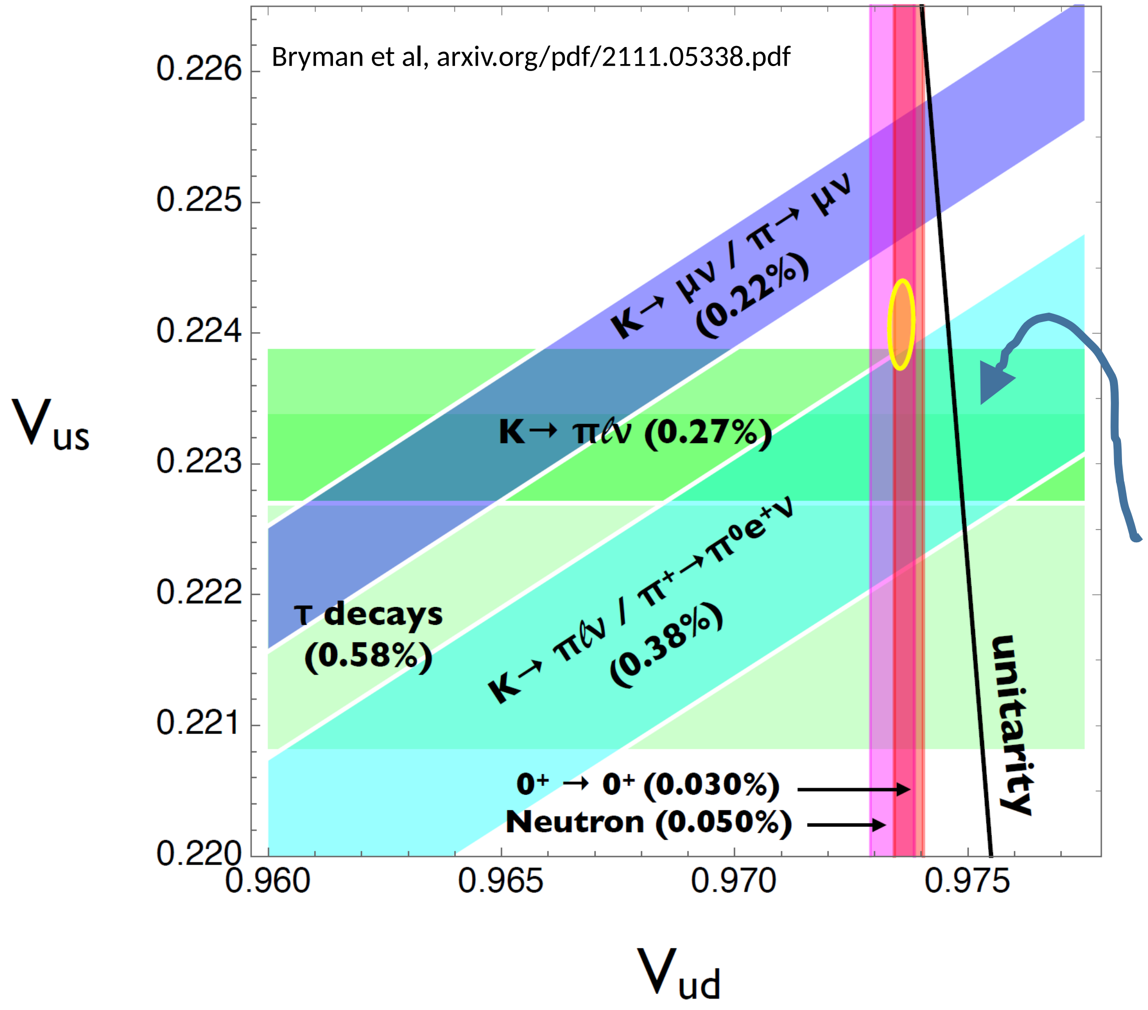
Will be (by far) the most precise test of Lepton Flavor Universality

Physics Case 2 (3): Improve pion beta decay by factor of 3 (10)

(note: This is a long term goal, representing Phase II of PIONEER)

Tensions in the first-row CKM unitarity test

Again a ~3σ problem (or even more)



Dominant uncertainty in $\delta|V_{ud}|$ are associated with hadronic and nuclear corrections

Pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ provides the theoretically cleanest determination of $|V_{ud}|$

BUT, uncertainty is too large at present.

New idea* , a 3-fold improvement (~doable) in pion beta decay, together with improved $K \to \pi \ell \nu(\gamma)$ Improves R_V as shown

Pion beta decay and Cabibbo-Kobayashi-Maskawa unitarity

Andrzej Czarnecki
Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1

William J. Marciano
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA

Alberto Sirlin
Department of Physics, New York University, 726 Broadway, New York, New York 10003, USA

See also A. Crivellin /arxiv.org/pdf/2207.02507.pdf

The basics of pion decay and the challenges

<u>Measurements:</u>

What a pion decays to "normally" $BR\left(\pi^+ \to \mu^+ \nu_\mu(\gamma)\right) = 0.999877 = \pm 0.0000004$

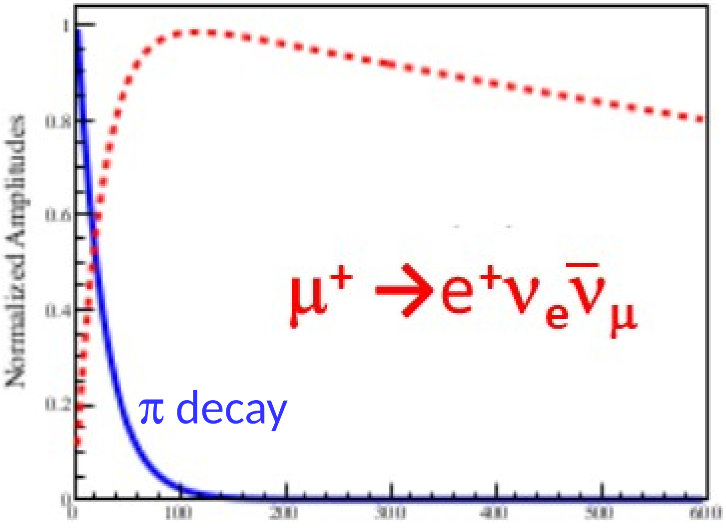
The helicity suppressed "e" branch $BR\left(\pi^+ \to e^+ \nu_e(\gamma)\right) = 1.2327 \pm 0.0023) \times 10^{-4}$

The "beta decay" branch $BR\left(\pi^+ \to e^+ \nu_e \pi^0\right) = 1.036 \pm 0.006) \times 10^{-8}$

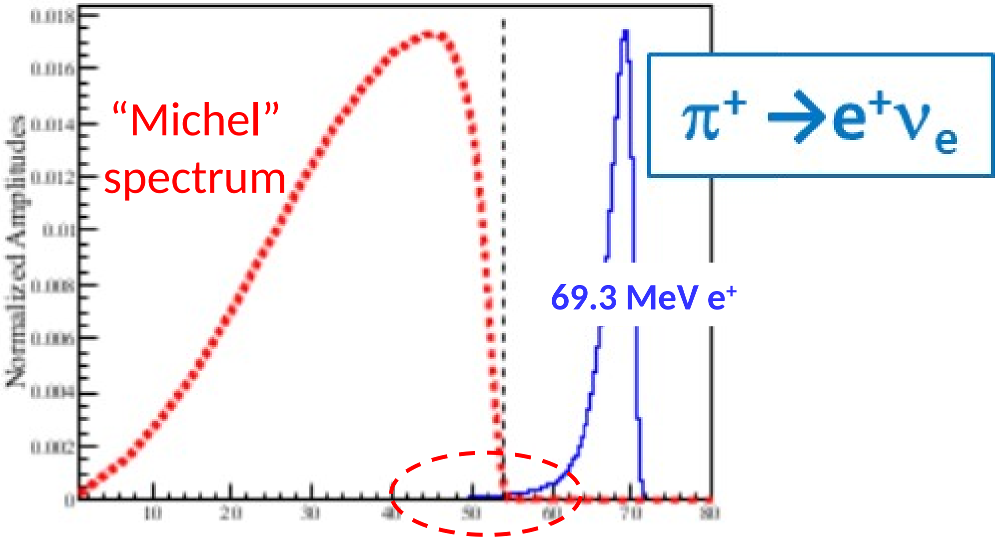
<u>Reminders:</u>

Pion lifetime: 26 ns
Muon lifetime: 2197 ns

Pion mass: 139.6 MeV
Muon mass: 105.7 MeV



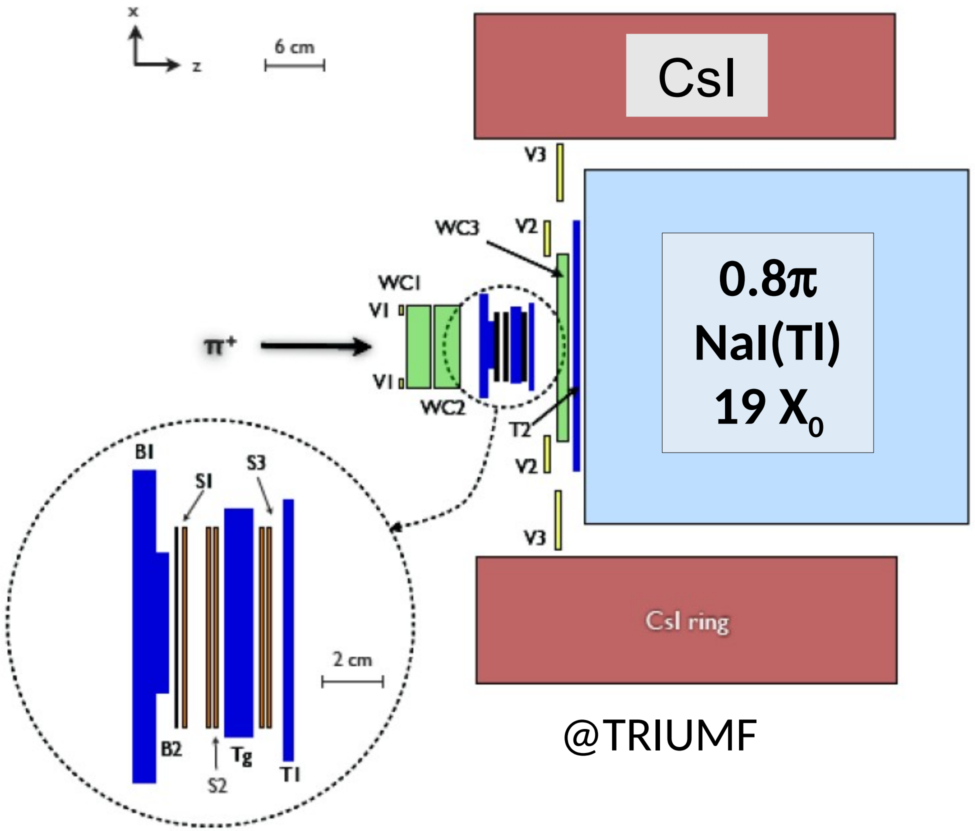
Timing



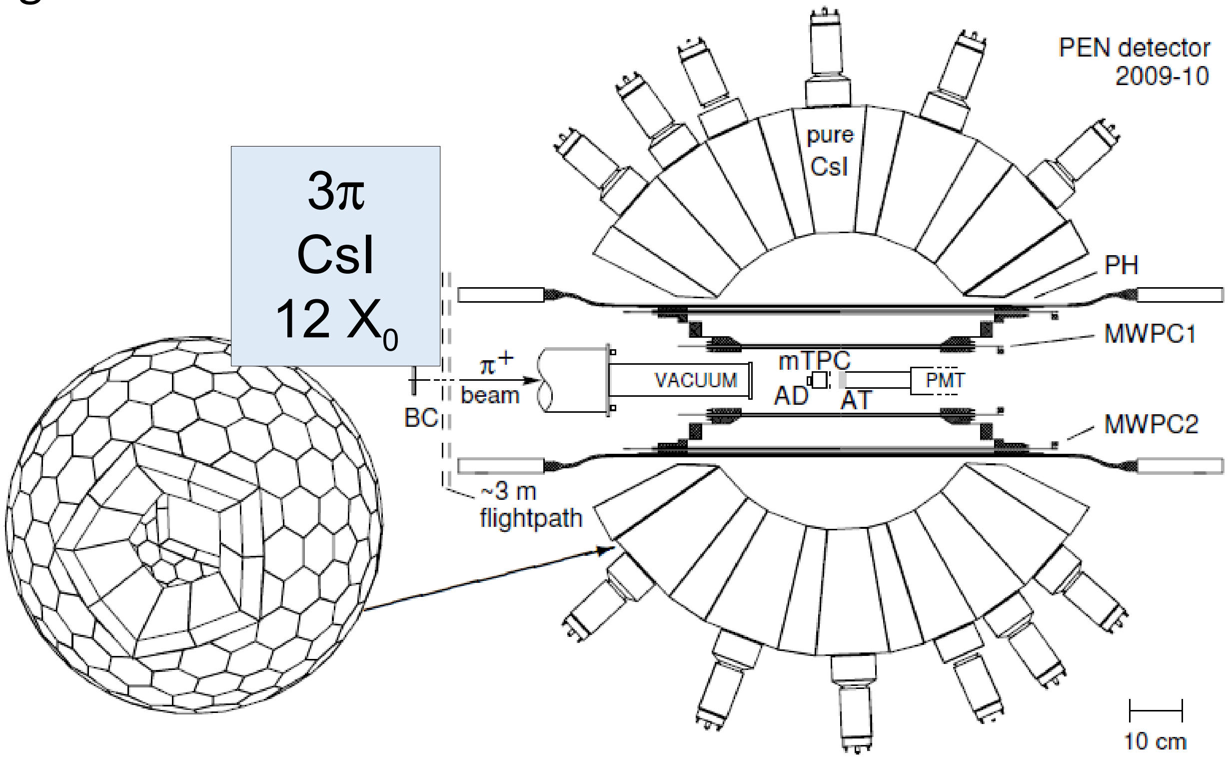
e^+ Energy

Two (rather different) Pion Decay Experiments: PIENU and PEN/PIBETA

Both took data a while ago but have (known) challenges to overcome before final results



@TRIUMF



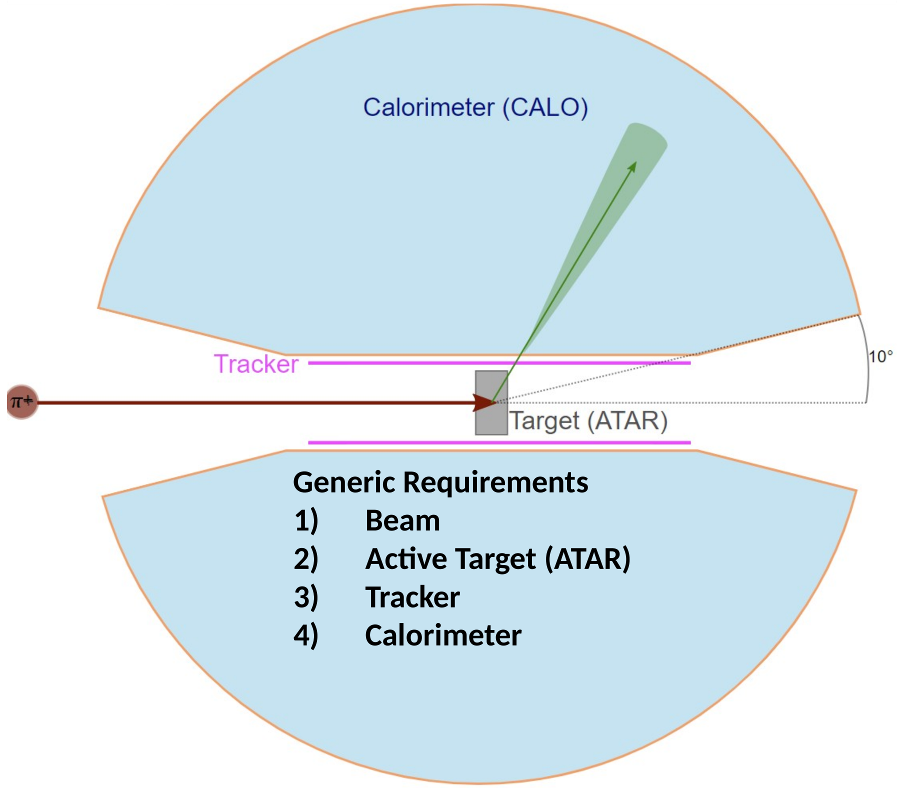
@PSI

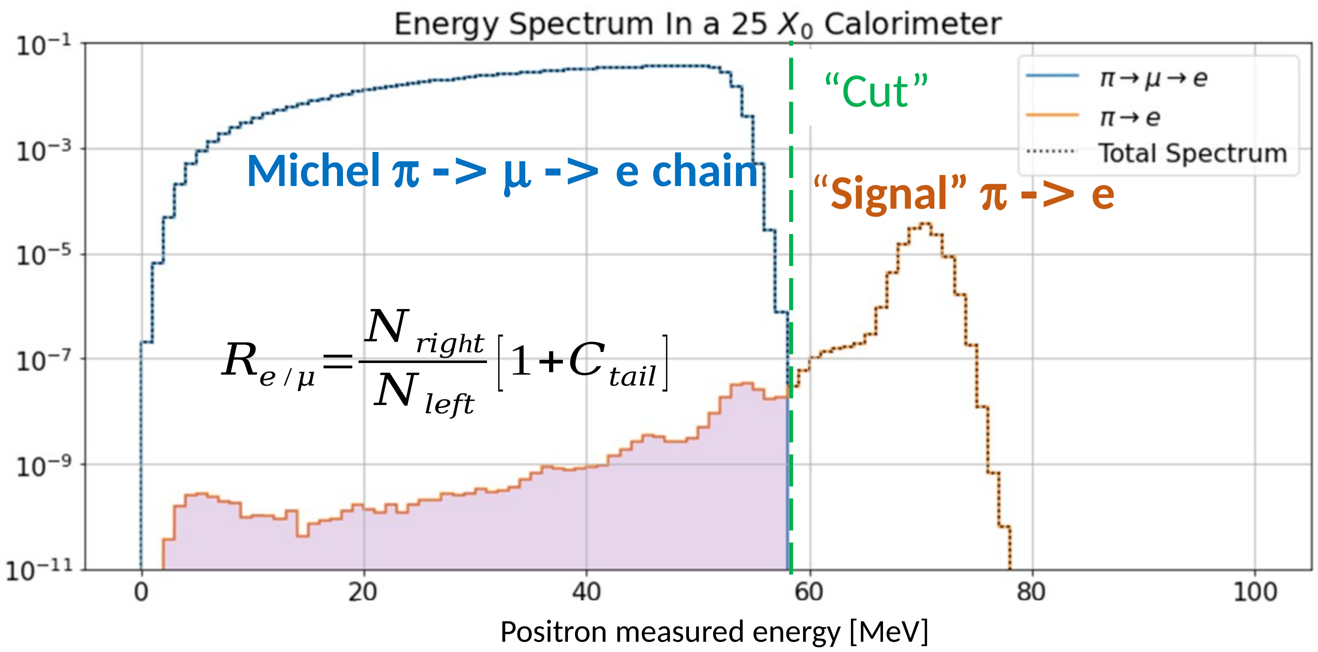
- NaI slow, but excellent resolution
- Single large crystal but shower leakage depends on angle changing resolution and tail fraction
- Small solid angle

- Good geometry but calorimeter depth of $12X_0$ too small to resolve tail under muon spectrum.

Generic experiment: count e⁺ from stopped π⁺ and sort:

$$\frac{N(\pi \to e\nu)}{N(\pi \to \mu\nu)} \to \frac{N(\pi \to e\nu)}{N(\pi \to \mu \to e\nu\nu)}$$





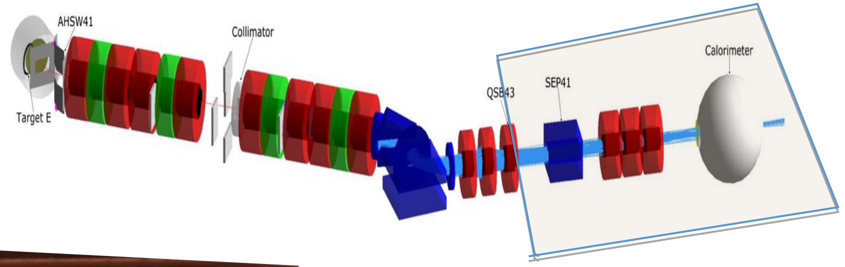
The mono-energetic 69 MeV "signal" spectrum is determined from

- Calo Resolution – better sharpens the "right/left" cut boundary
- Calo Depth – deeper minimizes the tail

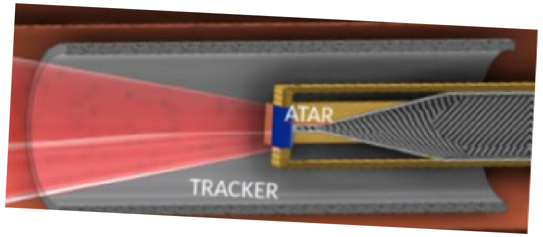
The key to success: minimize and measure the tail

Q: How can you possibly measure that tail under the Michel spectrum?

Technologies being explored

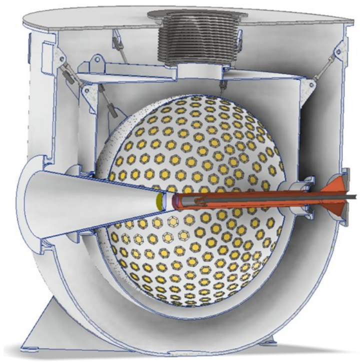


- World's most intense low-energy pion beamline at PSI

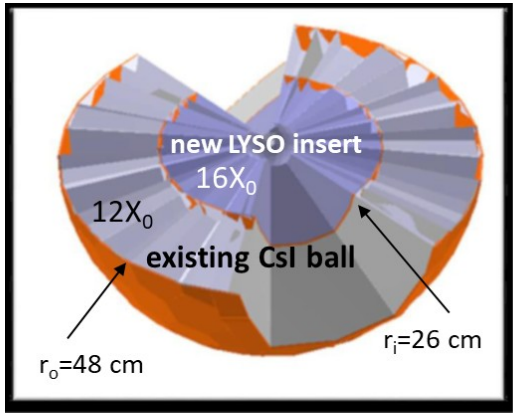


- Active, segmented target (ATAR) using AC LGADs
- Cylindrical tracker Resistive Micro Well (μ-RWELL)

  (or LGADs or silicon strip detectors



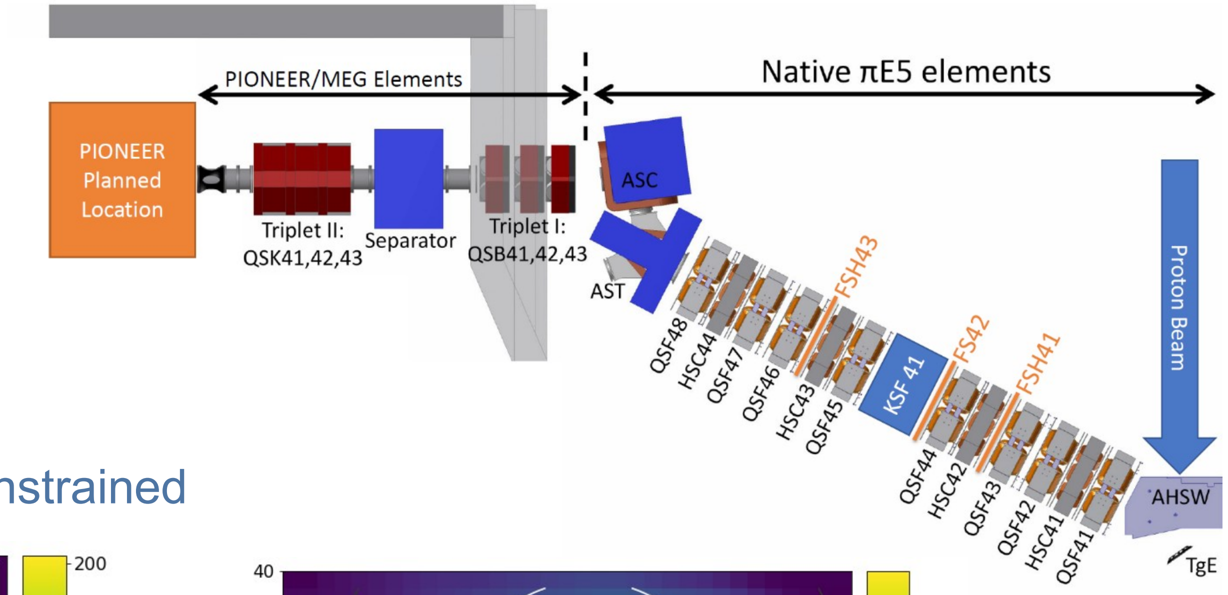
- Fast, deep, high-resolution calorimeter options
  - LXe following the example of the MEG II collaboration
  - Hybrid LYSO + CsI (existing) crystal combination

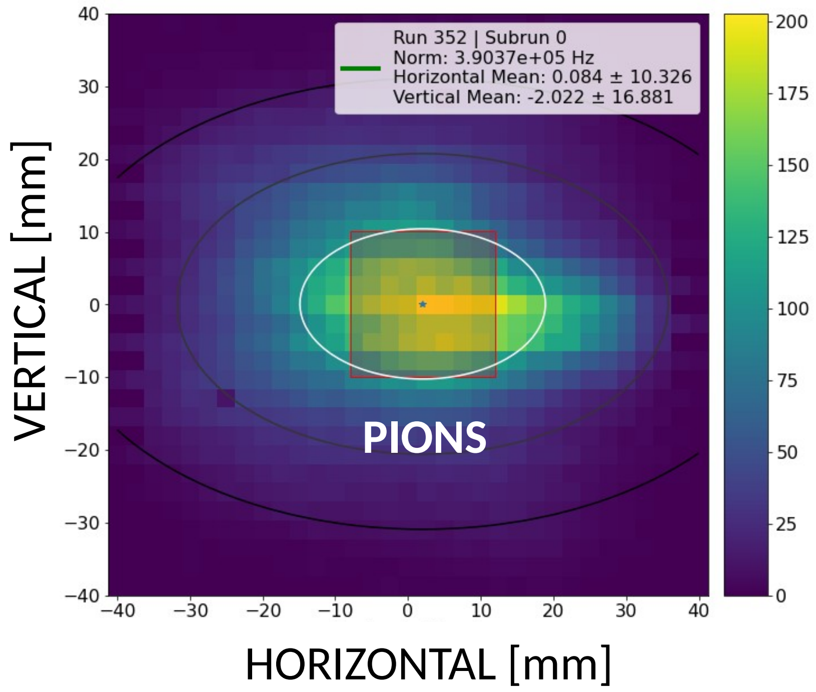


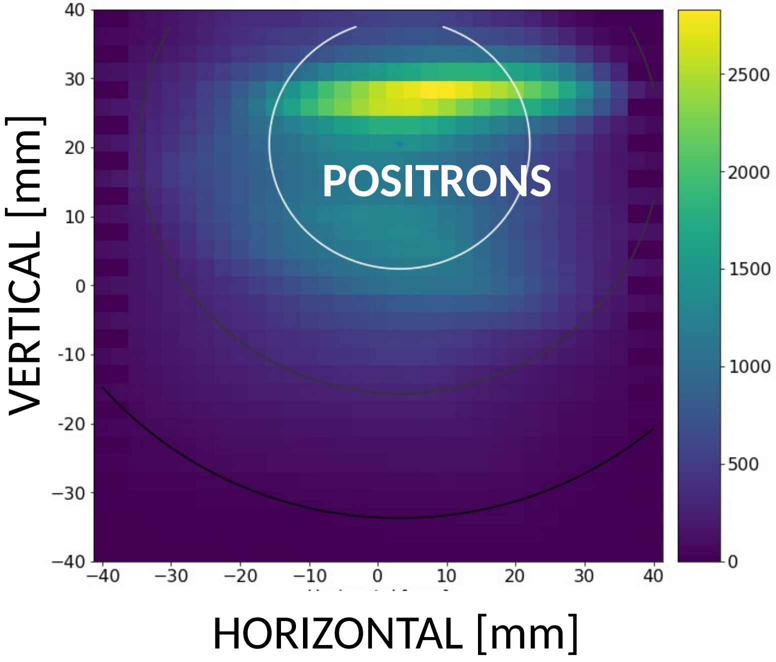
- And of course, very fast triggering, DAQ, high res digitization, etc.

Use World's Brightest Stopped Pion Beam @ PSI: piE5

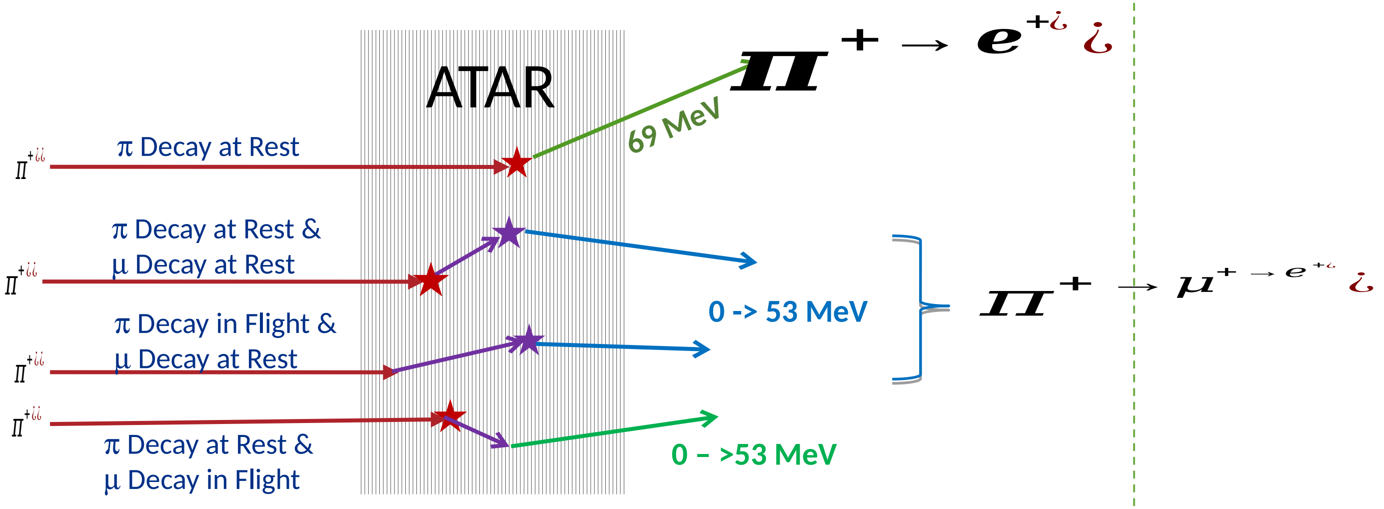
- Specifications (for Phase I) and first measurements
  - ✅ p = 55-70 MeV/c
  - ✅ σ_x, σ_y, < 10 mm and small divergence
  - 🚧 dp/p < 2% for top in 30.5 mm silicon
  - ✅ > 300 kHz stopping rate in target
  - 🚧 Separation of π / μ / e in beamline
- Going forward
  - Much to do to model and minimize spot size
  - Must add an intermediate focus, but space is constrained

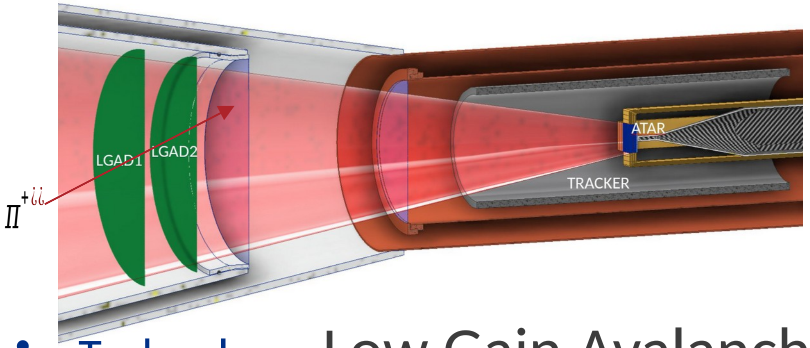


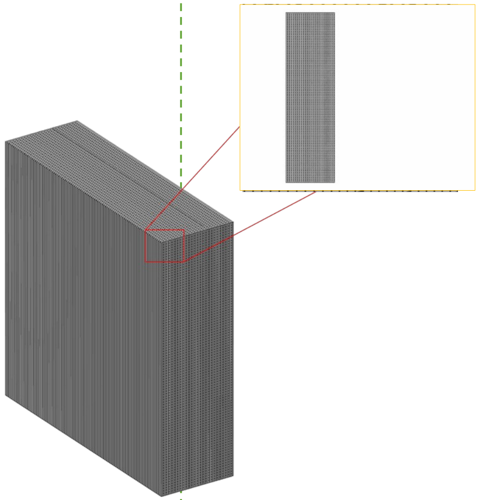


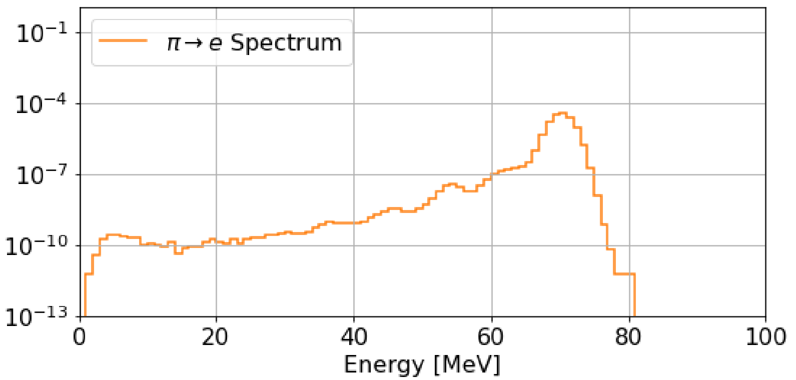


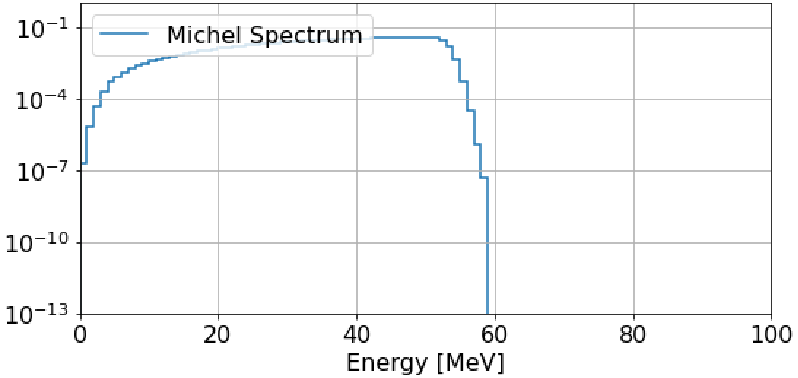
Spectrum and the background: ATAR

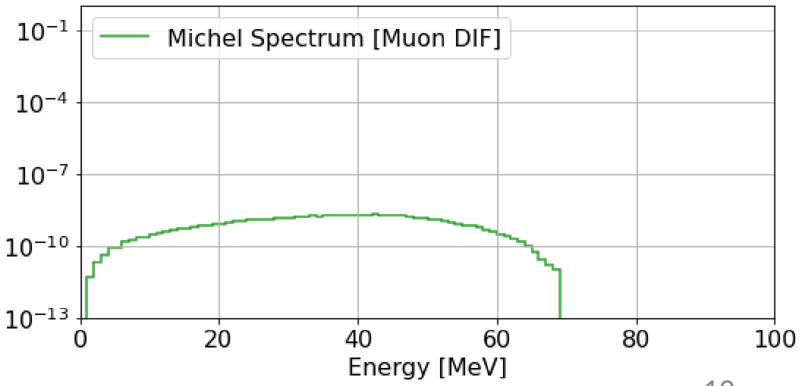








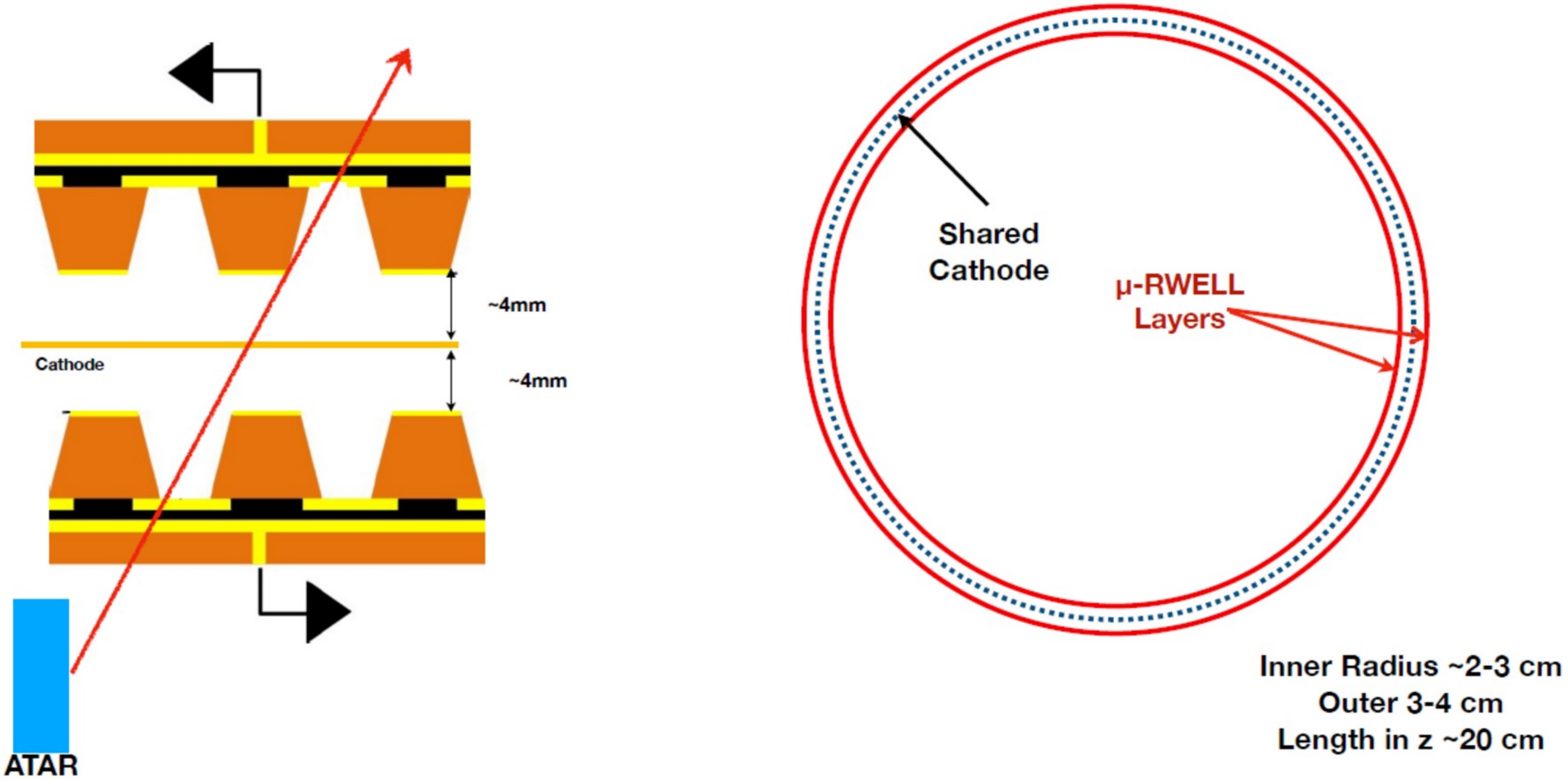




- Technology: Low Gain Avalanche
- Detectors LGADS
- Silicon detector
  - Thin, 120 um layers
  - Modest gain (10-50), σ_t < 100 ps with full charge collection ~ 2 ns
  - Intense R&D

Tracking positron to the calorimeter

Preliminary Idea for a Cylindrical μ-RWELL



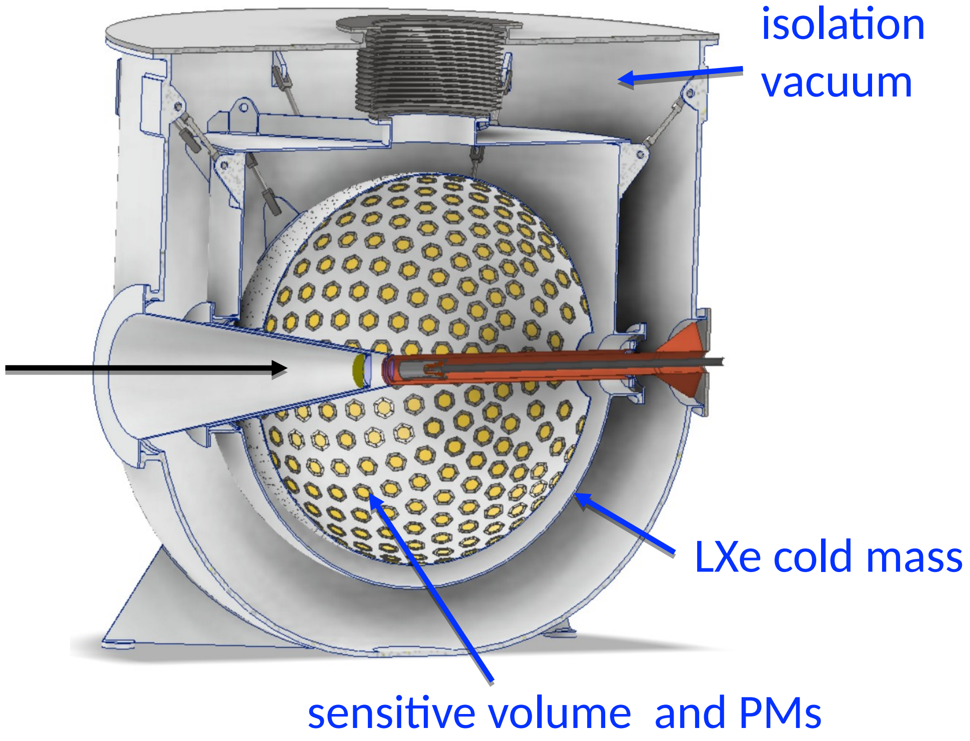
LXe Calorimeter is Baseline Design

- Based on MEG II Experience
  i. Fast: sub-ns timing, ~40 ns decay
  ii. Resolution <2% peak resolution

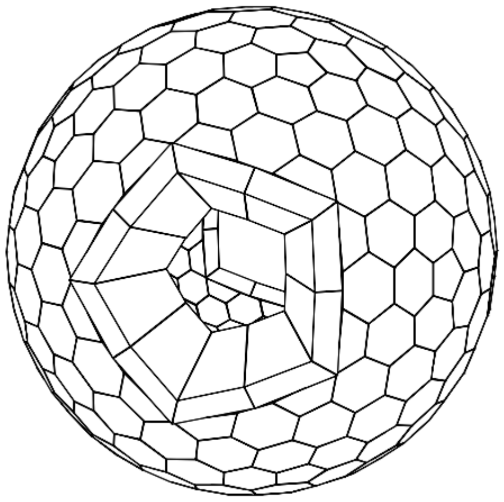
- LXe scintillating challenges
  – Optical segmentation
  – VUV Photosensors

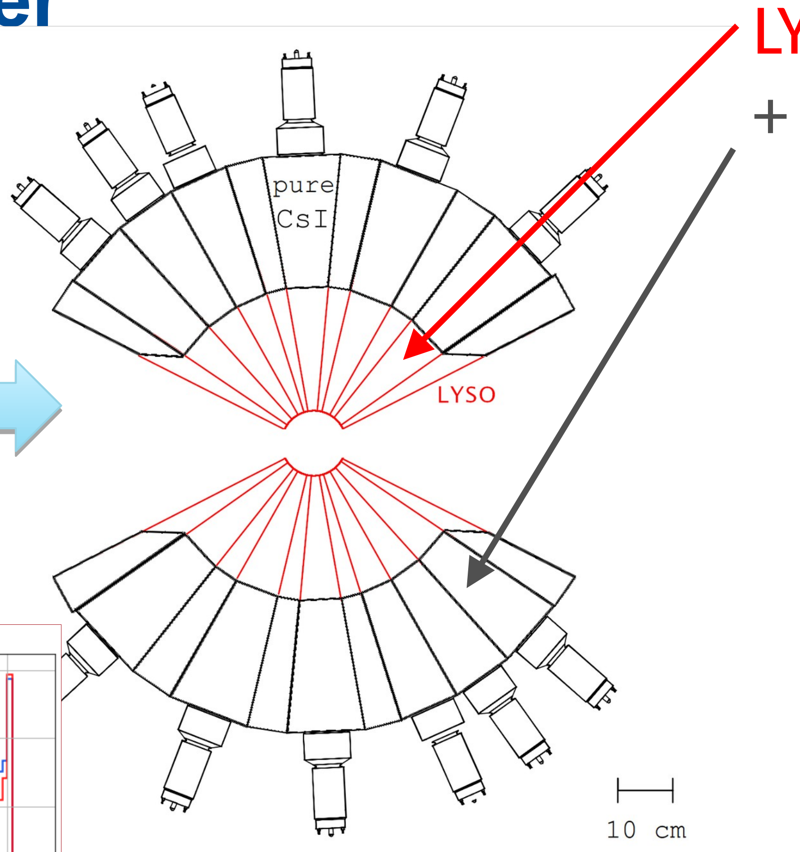
  –Major Challenge: LXe procurement!!

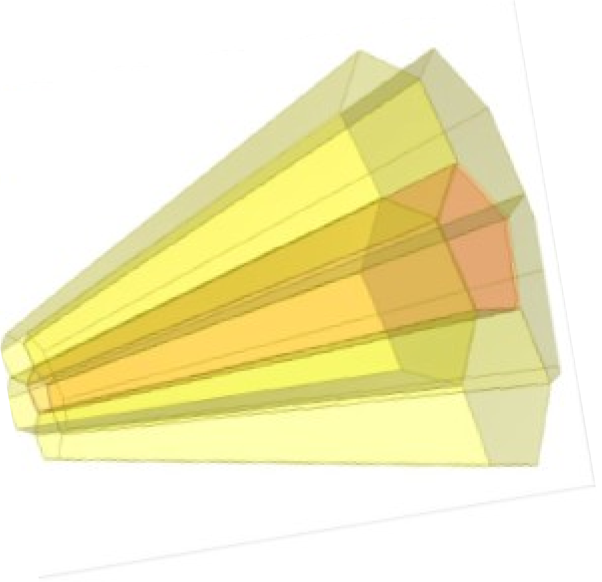
- Conceptual design
  – 9 t LXe sphere in vacuum isolated dewar
  – ~1000 VUV sensitive PMT readout
  – Possibly introduce segmentation

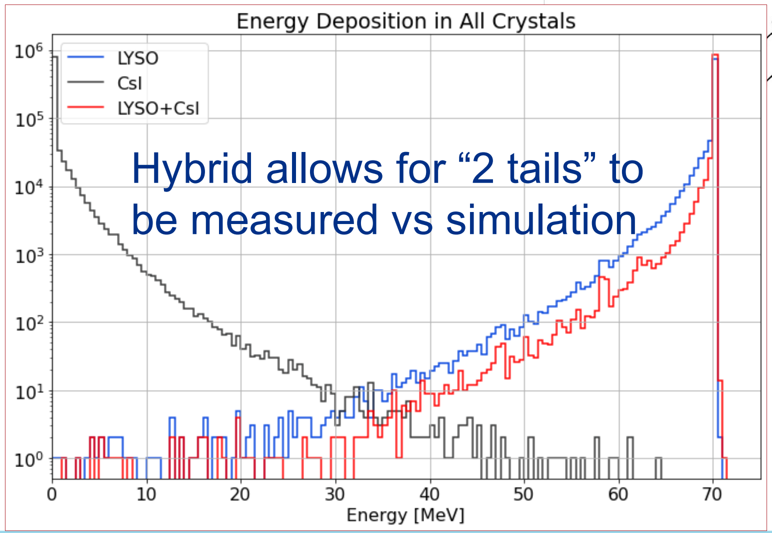


Crystal CALO alternative: New LYSO inner layer, matched to existing CsI (PEN) outer









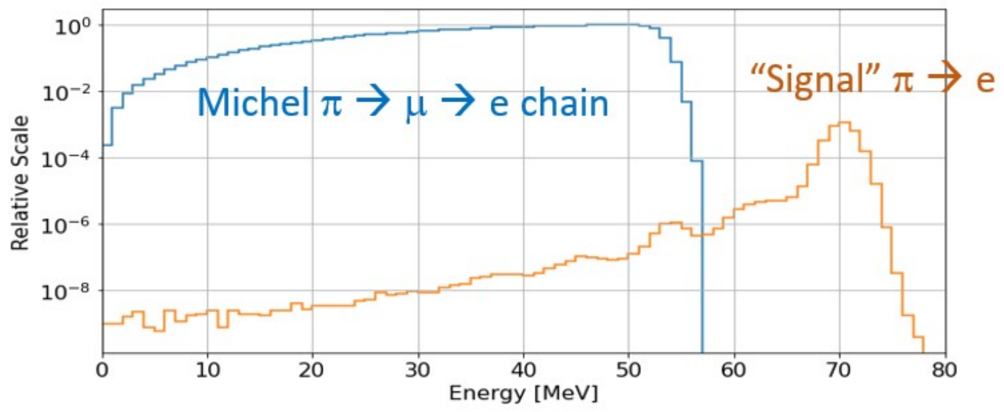
- Fast, segmented, compact, "cheaper"
- Is resolution good enough?
- LYSO for HEP not yet demonstrated, given its promise and extensive use in PET

Strategy for 10^{-4} precision experiment

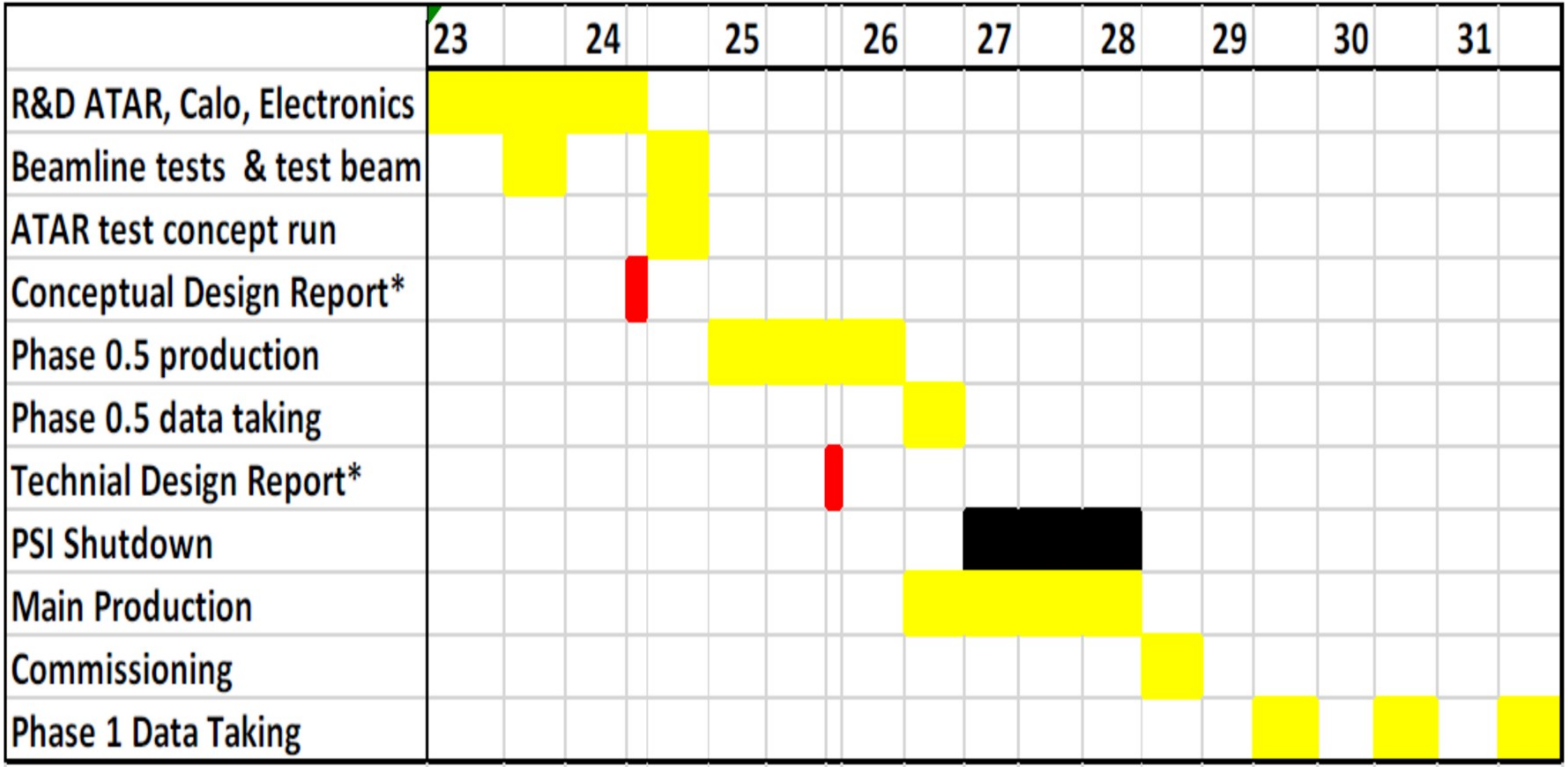
$$\sigma_{stat} = \sigma_{sys} = 0.7 \times 10^{-4}$$

- Analysis $R_{e/\mu} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$
  - fit high/low energy time distributions
    - background, pileup, etc
- Statistics
  - 2×10^{8} events in 2 years with 3×10^{5} /s beam
- Systematic improvements
  - intense, high quality beam
  - active target with key new ideas and technology
  - calorimeter: 3, $25X_0$, high res., fast

normalization & background



Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	**≤ 0.01**



*Approximate target dates; funding profile not folded in

Summary / Conclusions

- Lots of exciting physics to be explored with a Next-Gen Pion Decay Experiment
  - Lepton Flavor Universality Violation – possible connected to the "many" existing flavor anomalies
    - B decays; CKM, issues, Muon g-2, …
  - Measurement of Pion Beta Decay; ratio with kaon decays gives important slope in V_{ud} vs V_{us} plane
  - Exotic physics searches will come out automatically from these precision measurements
    - Sterile neutrinos, ALPs, etc.

  - PIONEER is APPROVED and is a growing international collaboration of physicists from broad communities in HEP, NP, instrumentation, theory
  - To be successful it will require:
    - State of the art active target with 4D tracking
    - Precise cylindrical tracker
    - A very high resolution, fast, and deep EM calorimeter
    - An intense stopping pion beamline
    - State of the art triggering, digitization, DAQ, and offline
    - Simulations, simulations, etc.

  - This is an exciting time with a new collaboration forming and a "semi-blank slate" to design a new experiment together

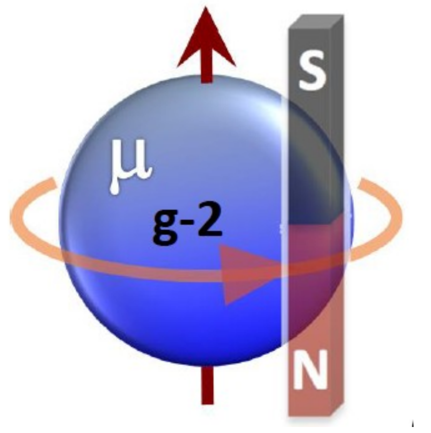
LINKS!

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

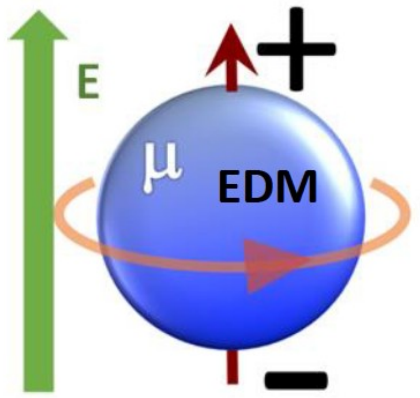
INFN reference: Angela Papa (Uni. and INFN Pisa)

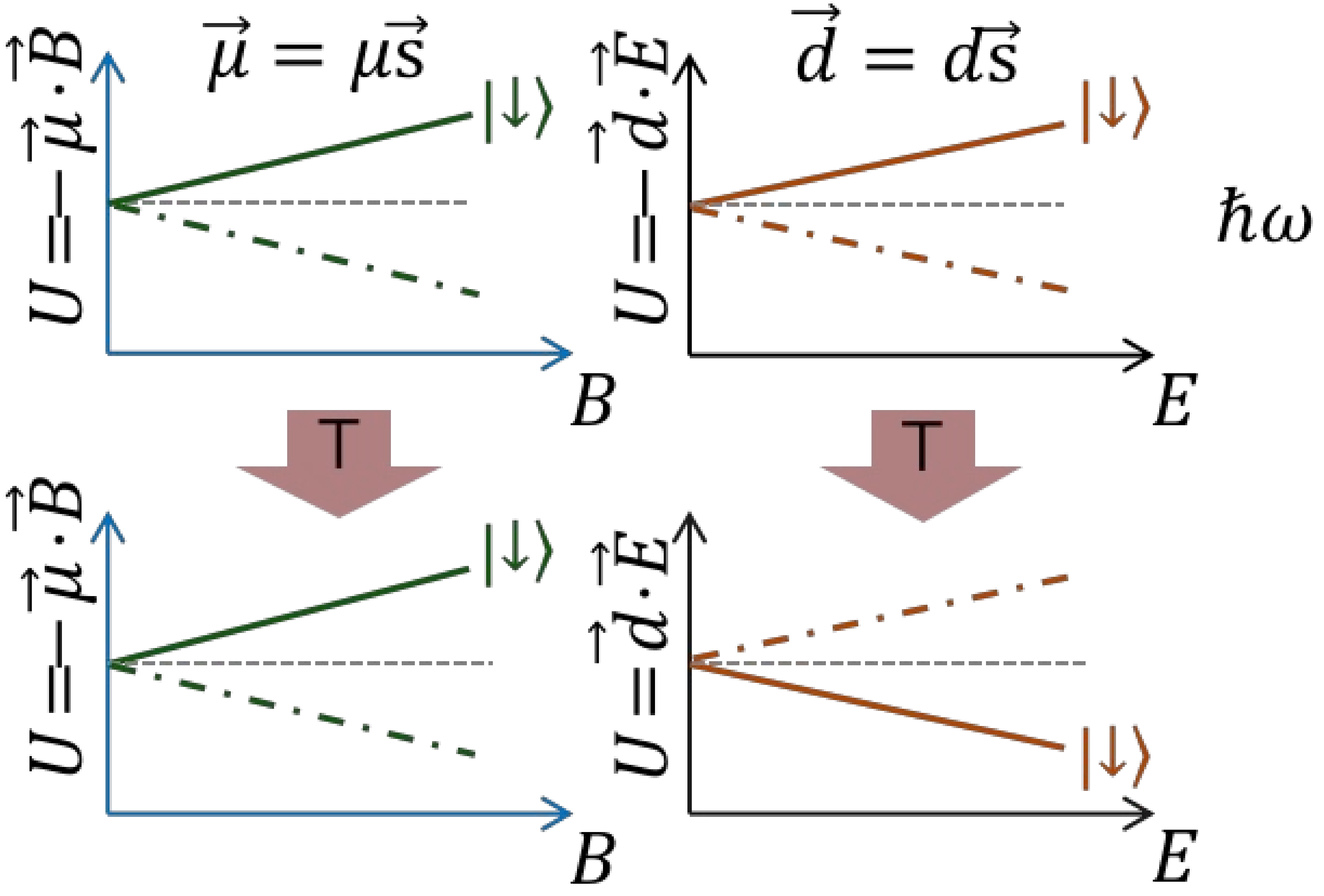
muEDM: Definition

Magnetic moment ($\boldsymbol{\mu}$ = gqh/4mc $\boldsymbol{\sigma}$)



Electric moment ($\mathbf{d}$ = ηqh/4mc $\boldsymbol{\sigma}$)





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

Search for a muon EDM using the frozen-spin technique

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

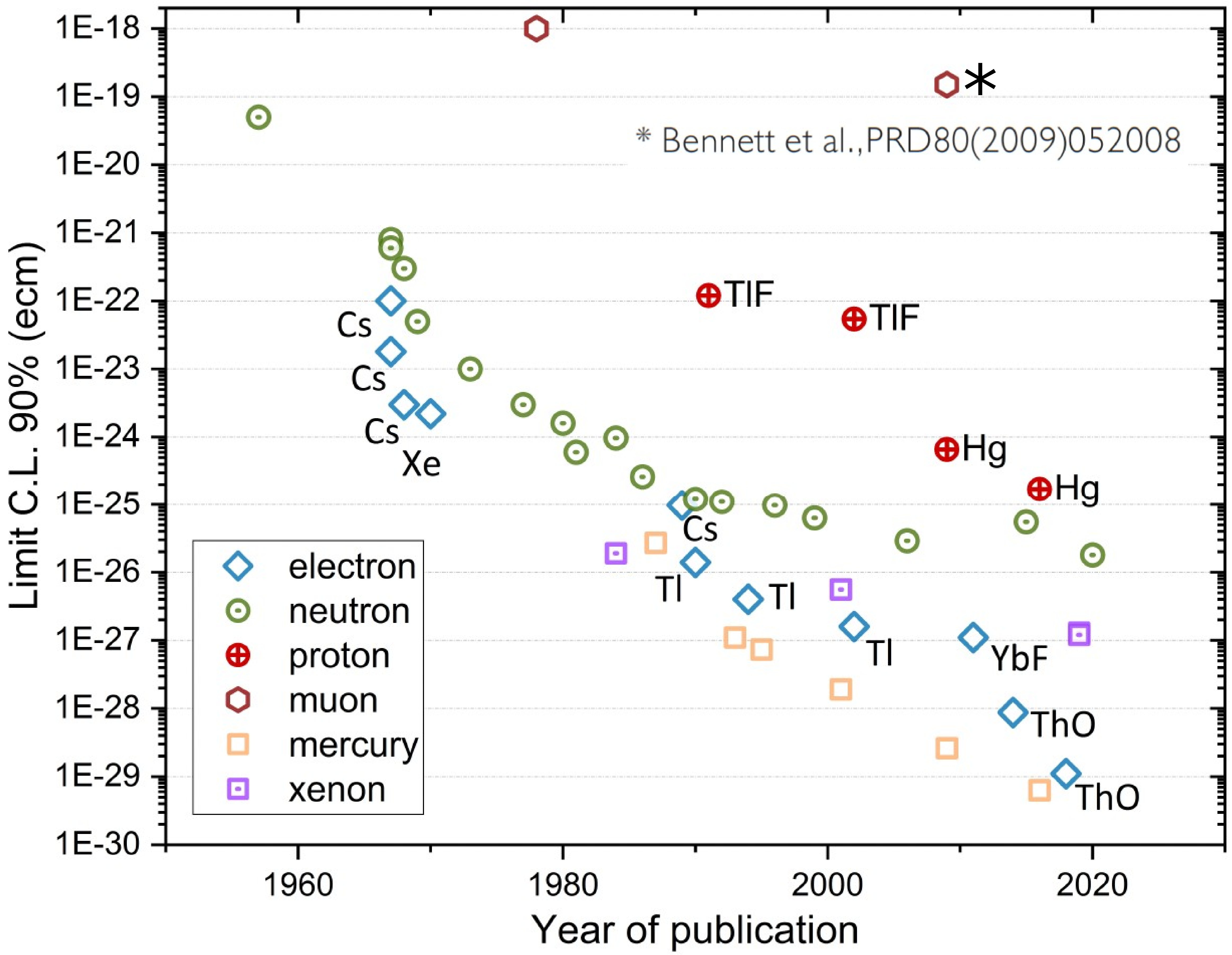
[1]*ETH Zürich, 8093 Zürich, Switzerland*
[2]*Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*
[3]*University of Liverpool, Liverpool, UK*
[4]*PRISMA+ Cluster of Excellence and Institute of Nuclear Physics, Johannes Gutenberg University Mainz, Mainz, Germany*
[5]*Sapienza Università di Roma, Dip. di Fisica, P.le A. Moro 2, 00185 Roma, Italy*
[6]*Istituto Nazionale di Fisica Nucleare, Sez. di Roma, P.le A. Moro 2, 00185 Roma, Italy*
[7]*University College London, London, UK*
[8]*CERN, 1211 Geneva, Switzerland*
[9]*University of Zürich, Zürich, Switzerland*
[10]*PRISMA+ Cluster of Excellence and Institute of Physics, Johannes Gutenberg University Mainz, Mainz, Germany*
[11]*Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany*
[12]*Department of Physics and Astronomy, University of Manchester, Manchester, UK*
[13]*Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China*
[14]*School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China*
[15]*Physik-Department, Technische Universität München, Garching, Germany*
[16]*Brookhaven National Laboratory, USA*
[17]*University of Pisa and INFN, Pisa, Italy*
[18]*RWTH Aachen, Aachen, Germany*
[19]*Physics Institute, Heidelberg University, Heidelberg, Germany*
[20]*Argonne National Laboratory, Lemont, USA*

This letter of intent proposes an experiment to search for an electric dipole moment of the muon based on the frozen-spin technique. We intend to exploit the high electric field, $E = 1\,\mathrm{GV/m}$, experienced in the rest frame of the muon with a momentum of $p = 125\,\mathrm{MeV}/c$ when passing through a large magnetic field of $|\vec{B}| = 3\,\mathrm{T}$. Current muon fluxes at the μE1 beam line permit an improved search with a sensitivity of $\sigma(d_\mu) \leq 6 \times 10^{-23}\,e\cdot\mathrm{cm}$, about three orders of magnitude more sensitivity than for the current upper limit of $|d_\mu| \leq 1.8 \times 10^{-19}\,e\cdot\mathrm{cm}$ (C.L. 95%). With the advent of the new high intensity muon beam, HIMB, and the cold muon source, muCool, at PSI the sensitivity of the search could be further improved by tailoring a re-acceleration scheme to match the experiments injection phase space. While a null result would set a significantly improved upper limit on an otherwise un-constrained Wilson coefficient, the discovery of a muon EDM would corroborate the existence of physics beyond the Standard Model.

Keywords:

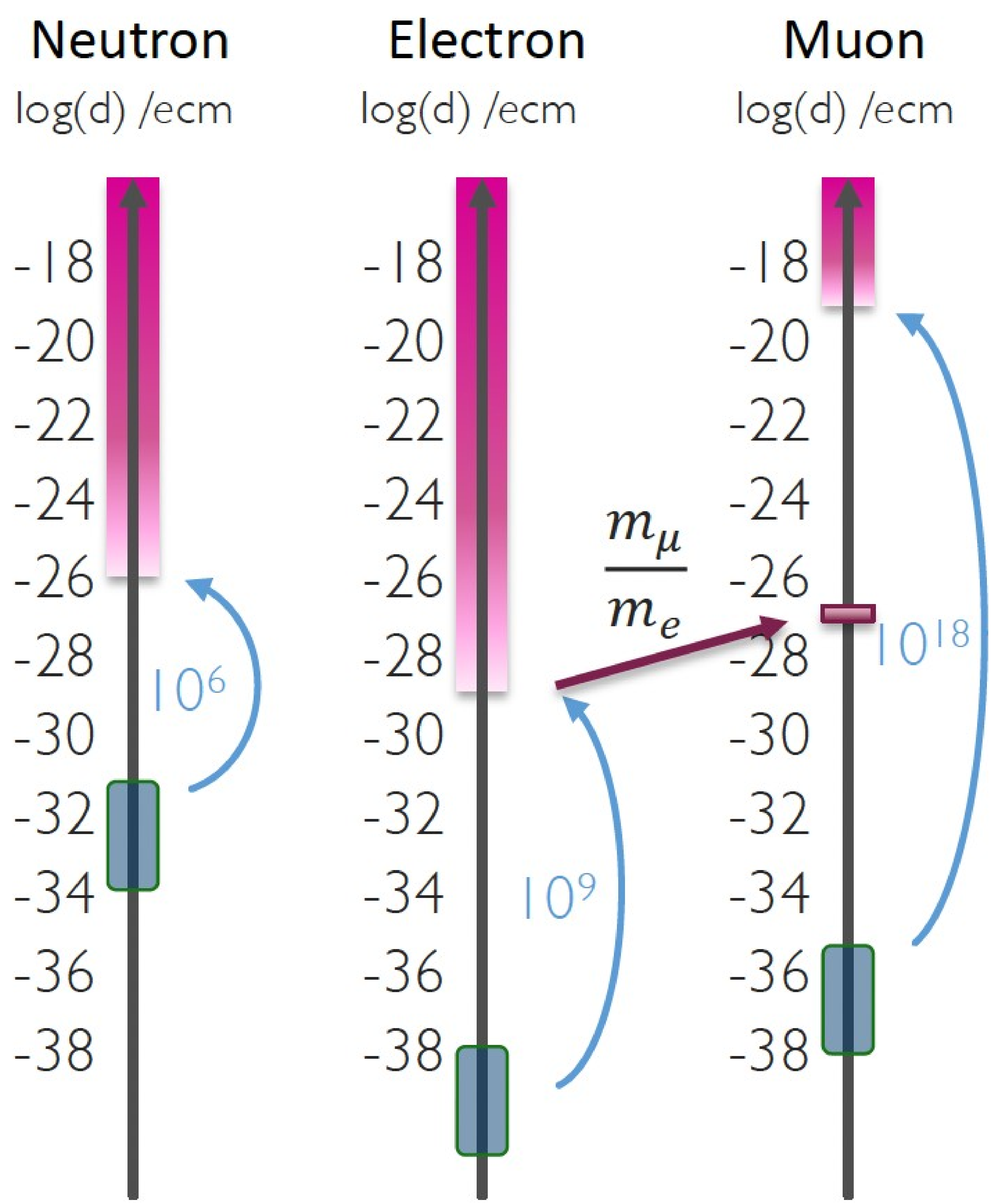
muEDM dedicated search: Current status

- 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?



- Limits on the electron EDM deduced from measurements using atoms or molecules, e.g., ThO molecules $d_e < 1.1\times10^{-29}\ e$cm (CL 90%) lead to $d_\mu < 2.3\times10^{-27}\ e$cm (CL 90%), many orders of magnitude better than the direct limit d_μ assuming m_μ/m_e naive rescaling minimal flavor violation (MFV),a model dependent assumption

- Experimental evidence found for deviation from SM physics involves the muo: g-2 experiment at FNAL ($a = (g-2)/2$ —> 4.2σ)

LFU in B-meson decays (3.1σ, more than 5σ 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 $4\ \sigma$)

- FNAL/JPARC g-2 experiments aims at d_μ ~ **O(10^{-21}) $e$cm (via g-2)**

- **Direct muEDM search at PSI in stages:**

  - **Precursors:** d_μ **< 3×10^{-21} $e$cm**

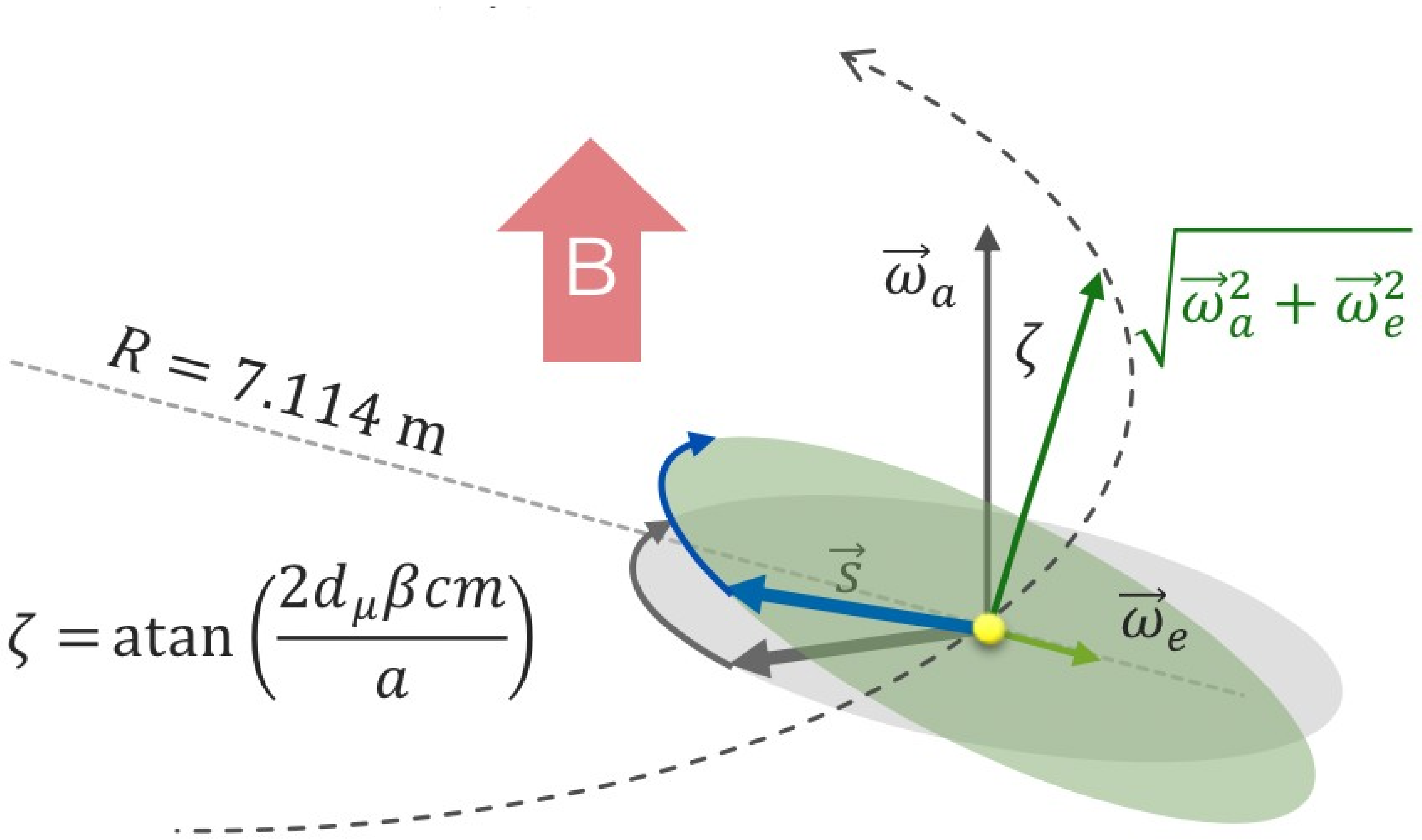
  - **Final:−::** d_μ **< 6×10^{-23} $e$cm**

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

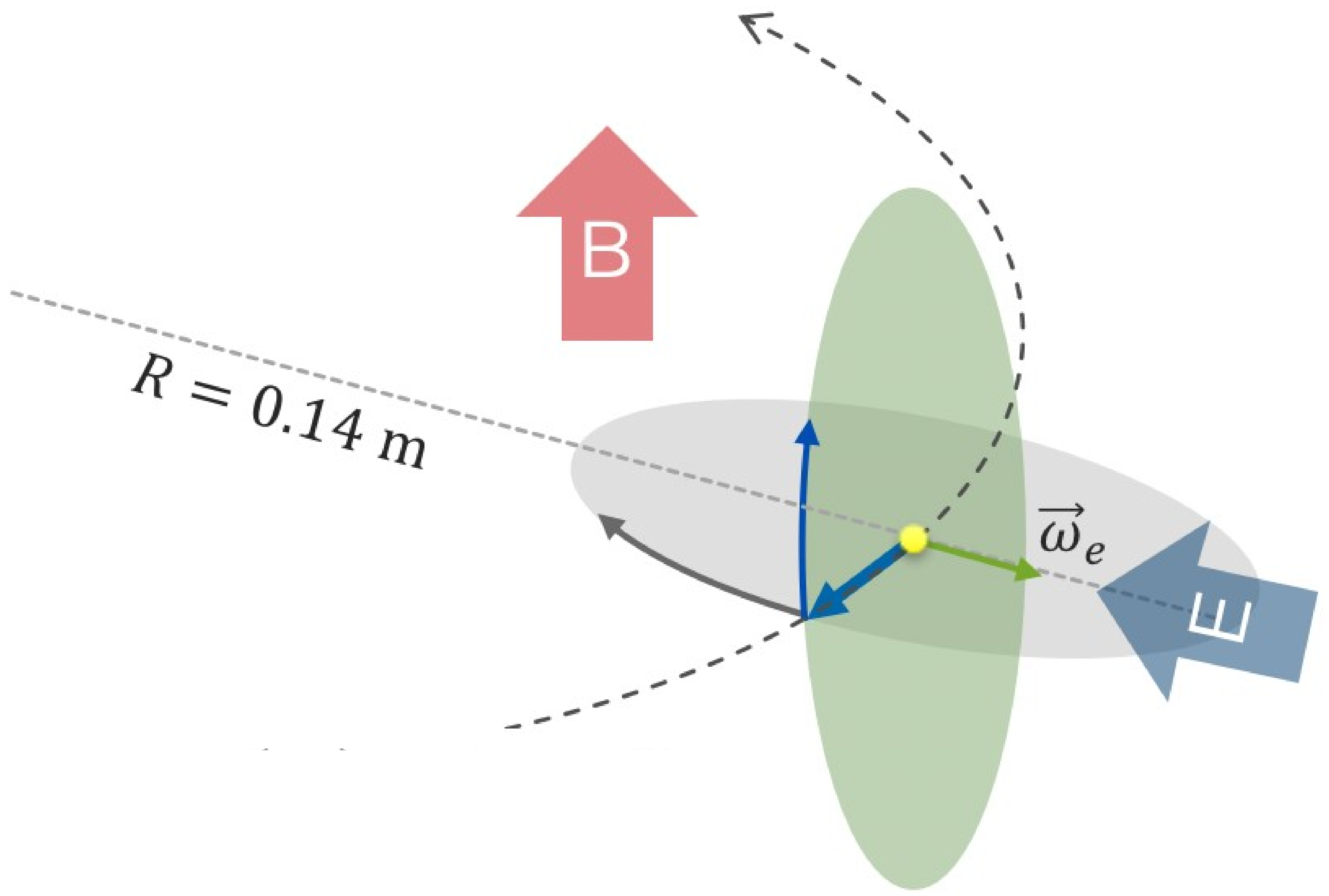
$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

ω_a ω_e

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

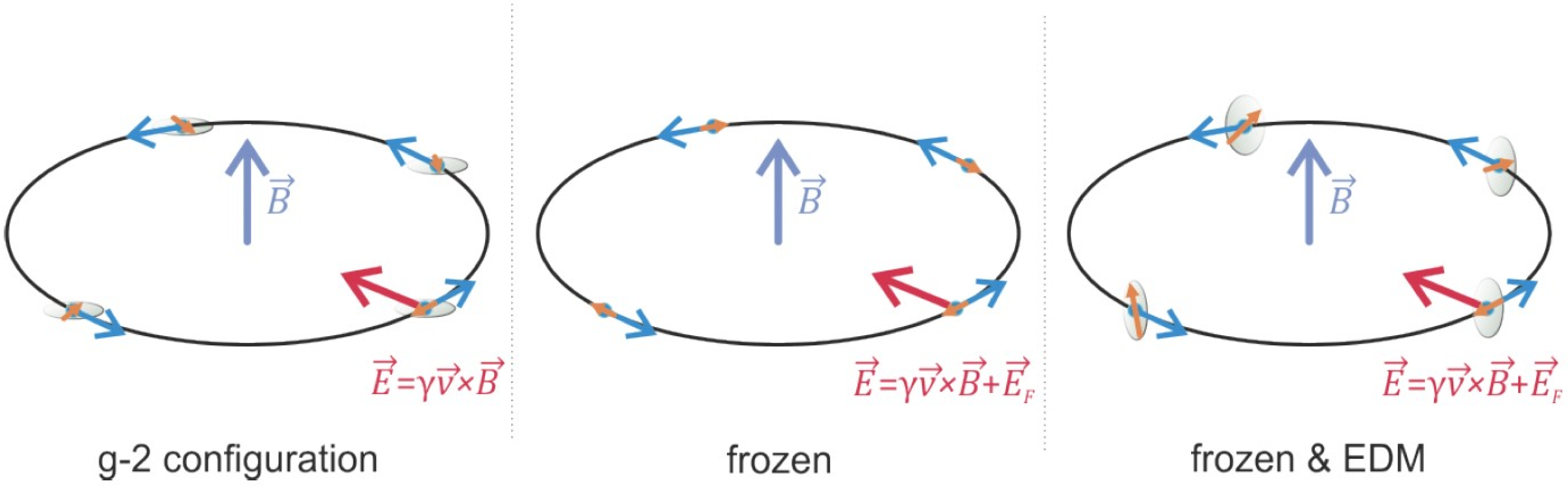
$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}_f}{c}$$

- 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 ω_e || 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

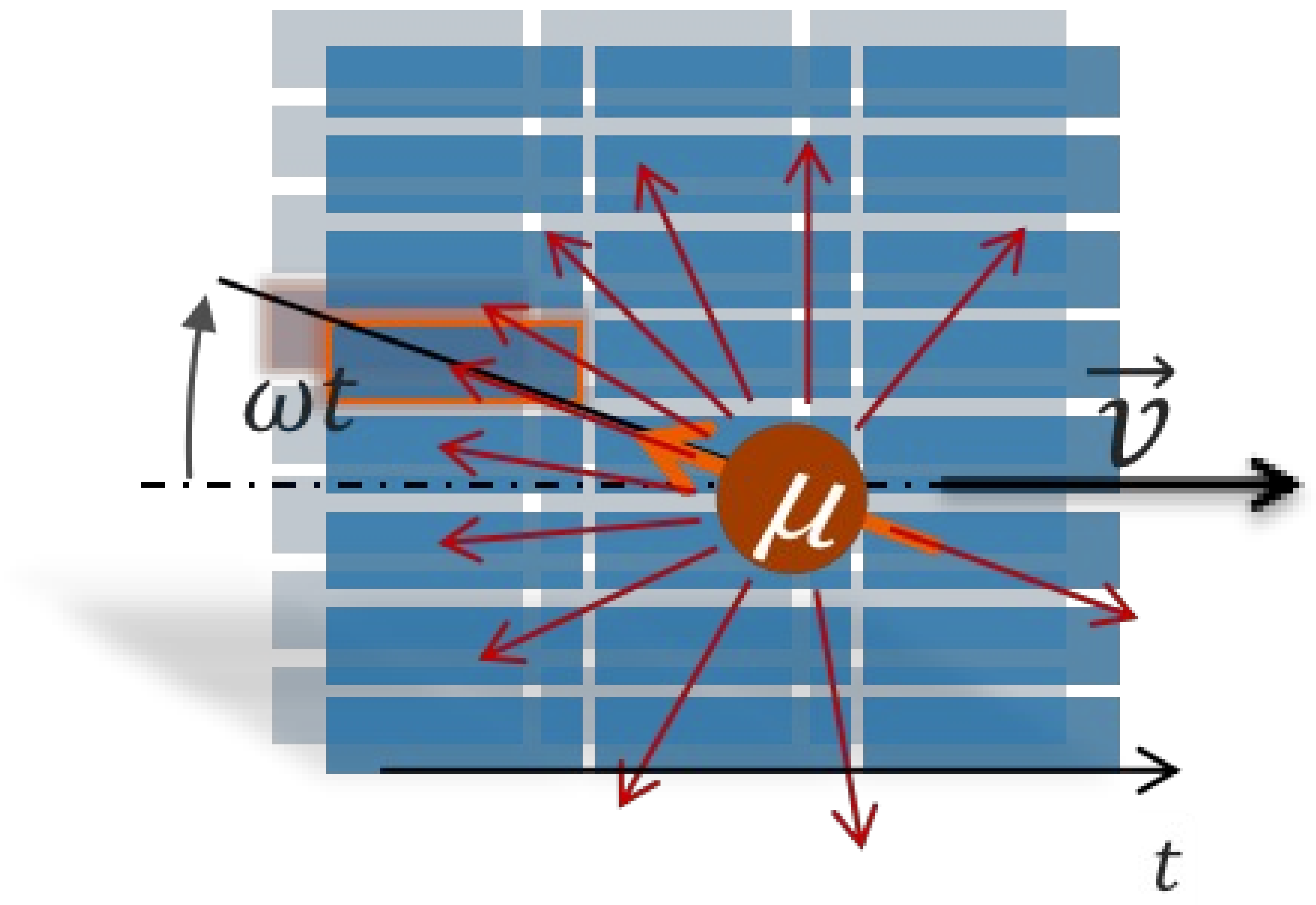
- Putting everything together, here a summary:

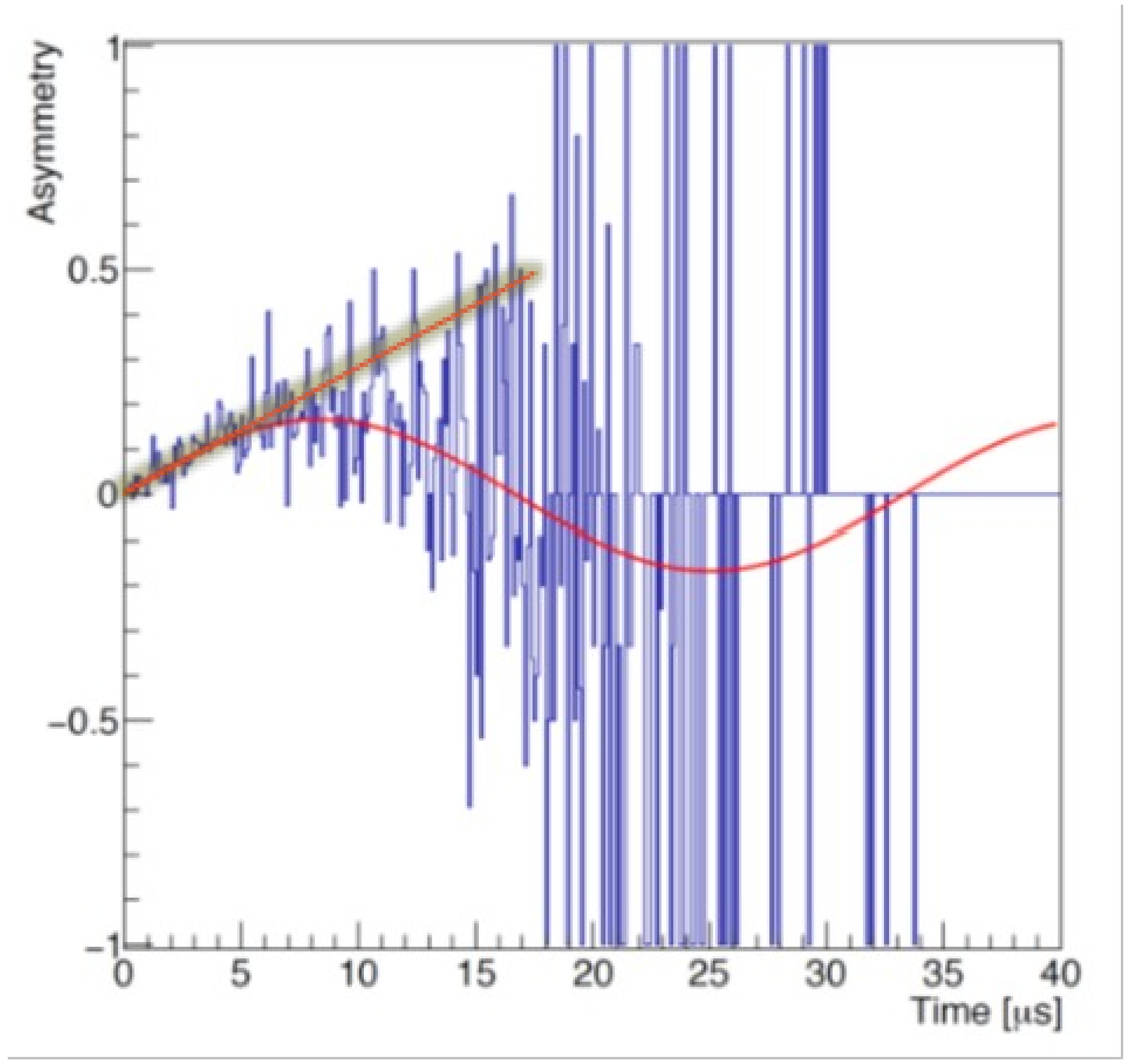


Signal: asymmetry up/down positron tracks

- 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

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





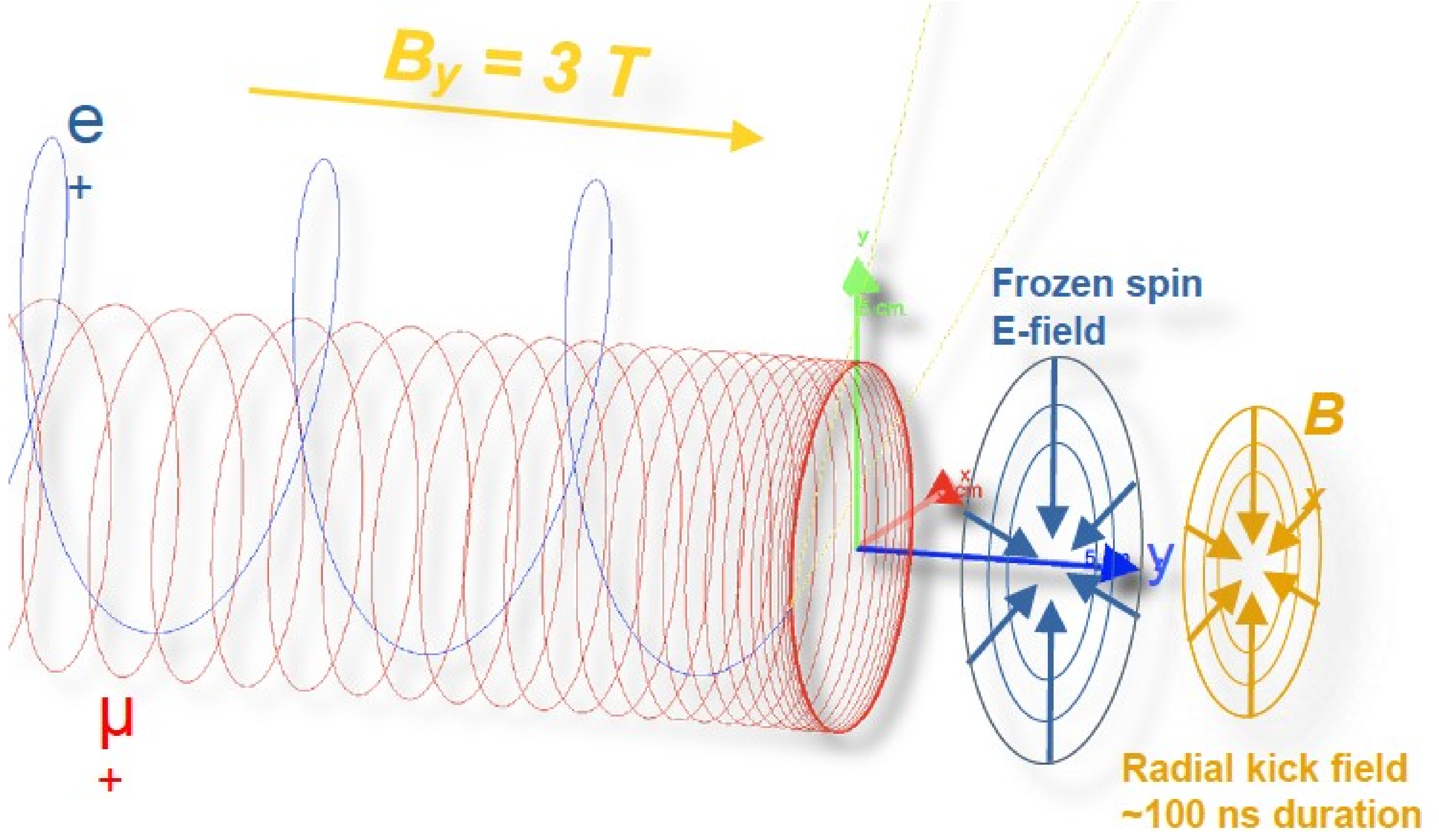
The slope gives the sensitivity of the measurement:

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

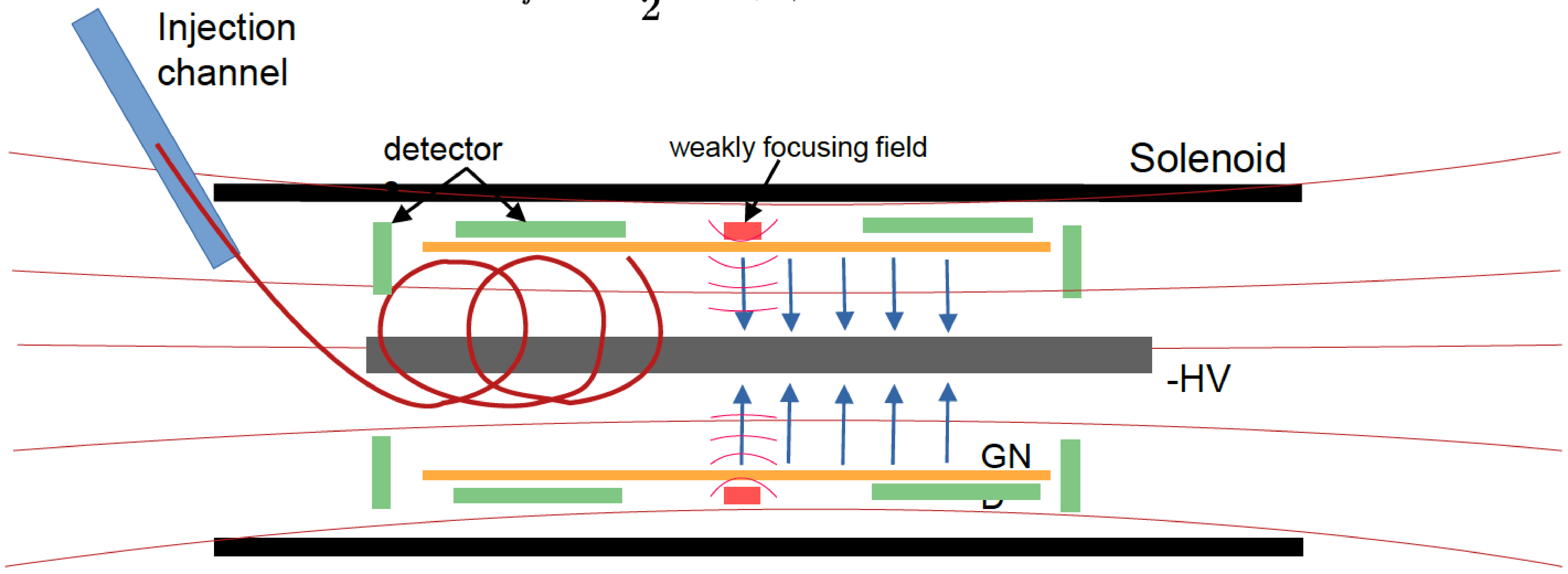
p := initial polarization
E_f := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_μ := lifetime of muon
α := mean decay asymmetry

The general experimental idea

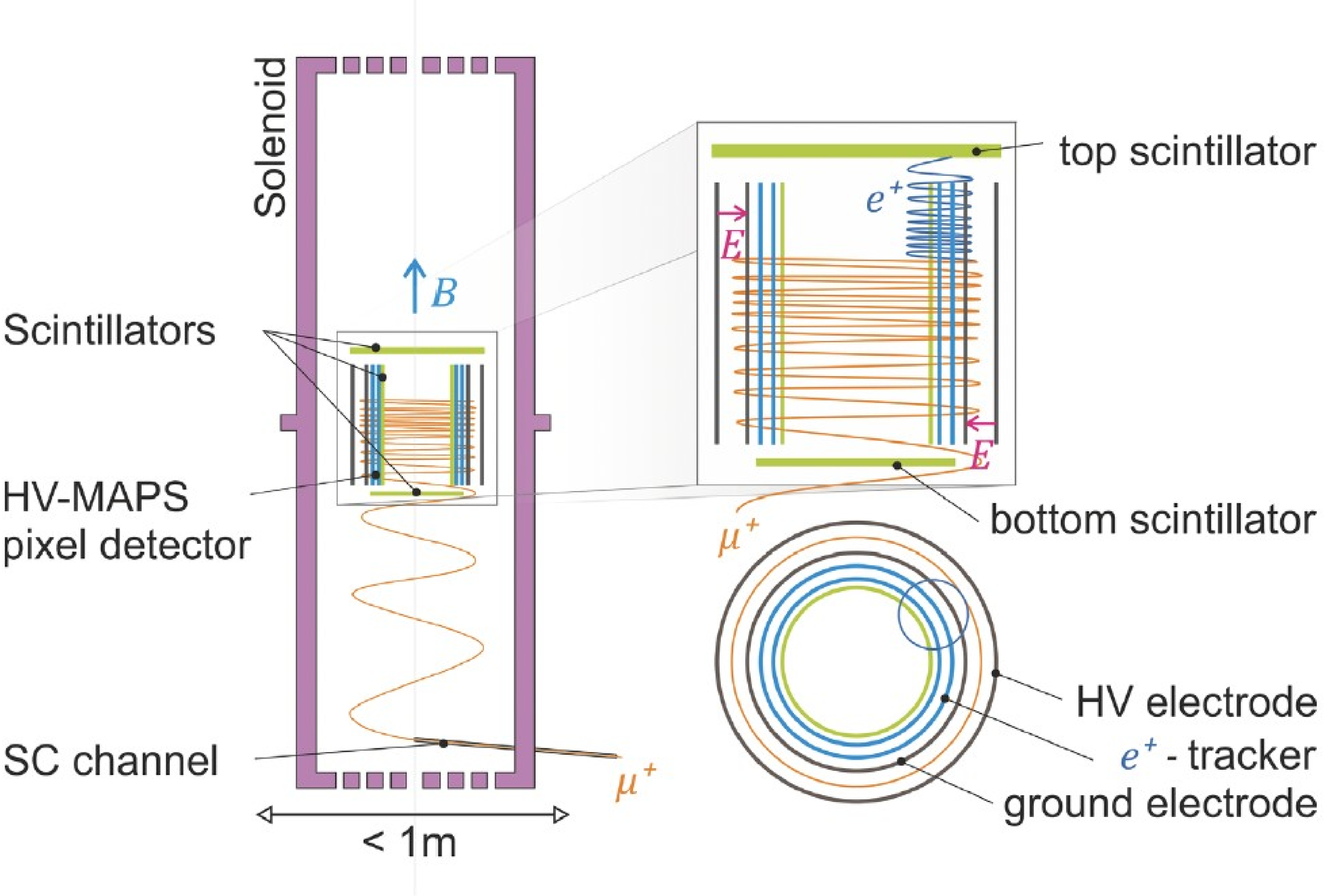
- Muons enter the uniform magnetic field
- A radial magnetic field pulse stops them within a weakly focusing field where they are stored
- Radial electric field 'freezes' the spin so that the precession due to the MDM is cancelled



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



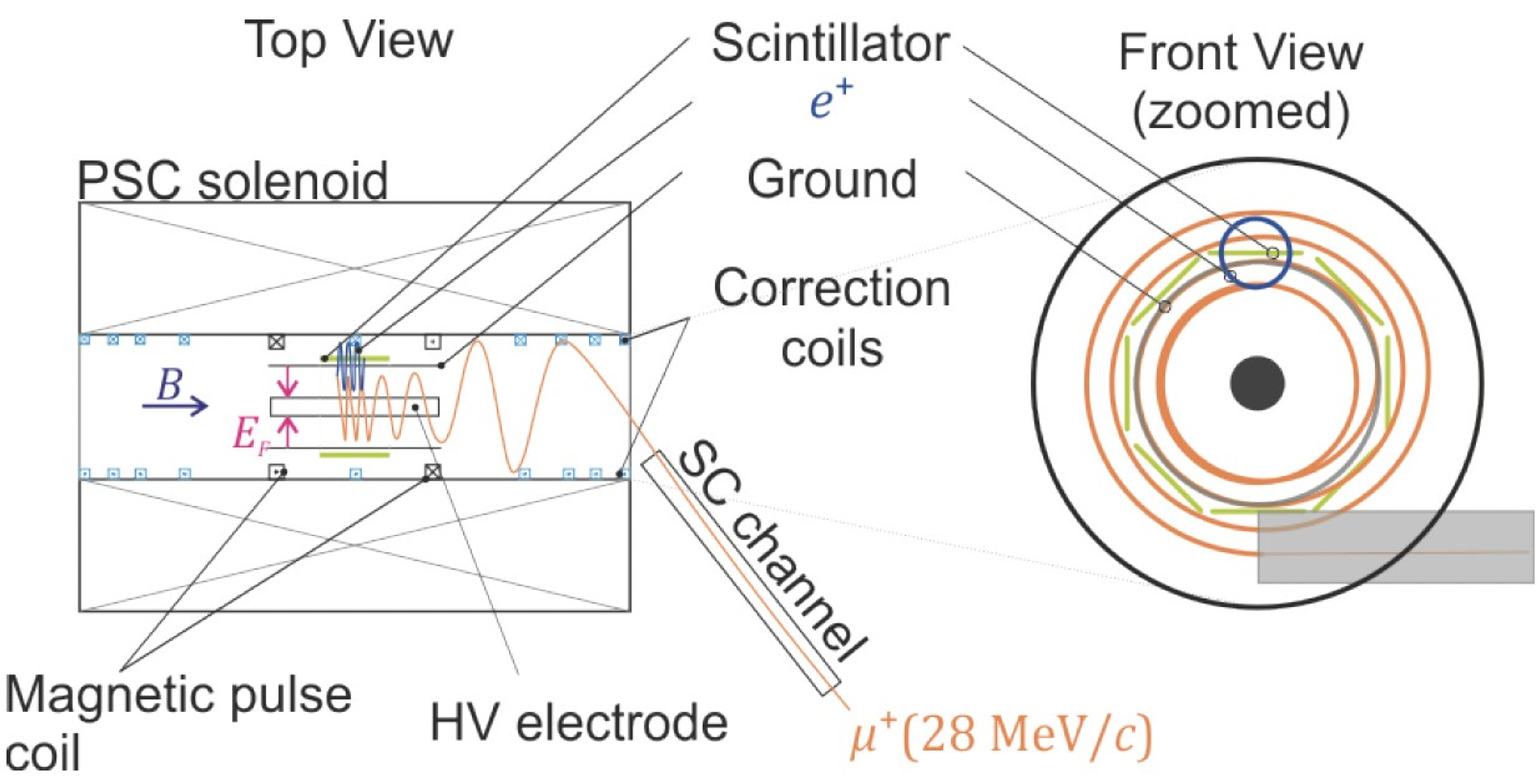
muEDM final at PSI: Frozen spin and longitudinal injection



p=125 MeV/c [muE1]

- μ^+ from Pion–decay $\rightarrow$ 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 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

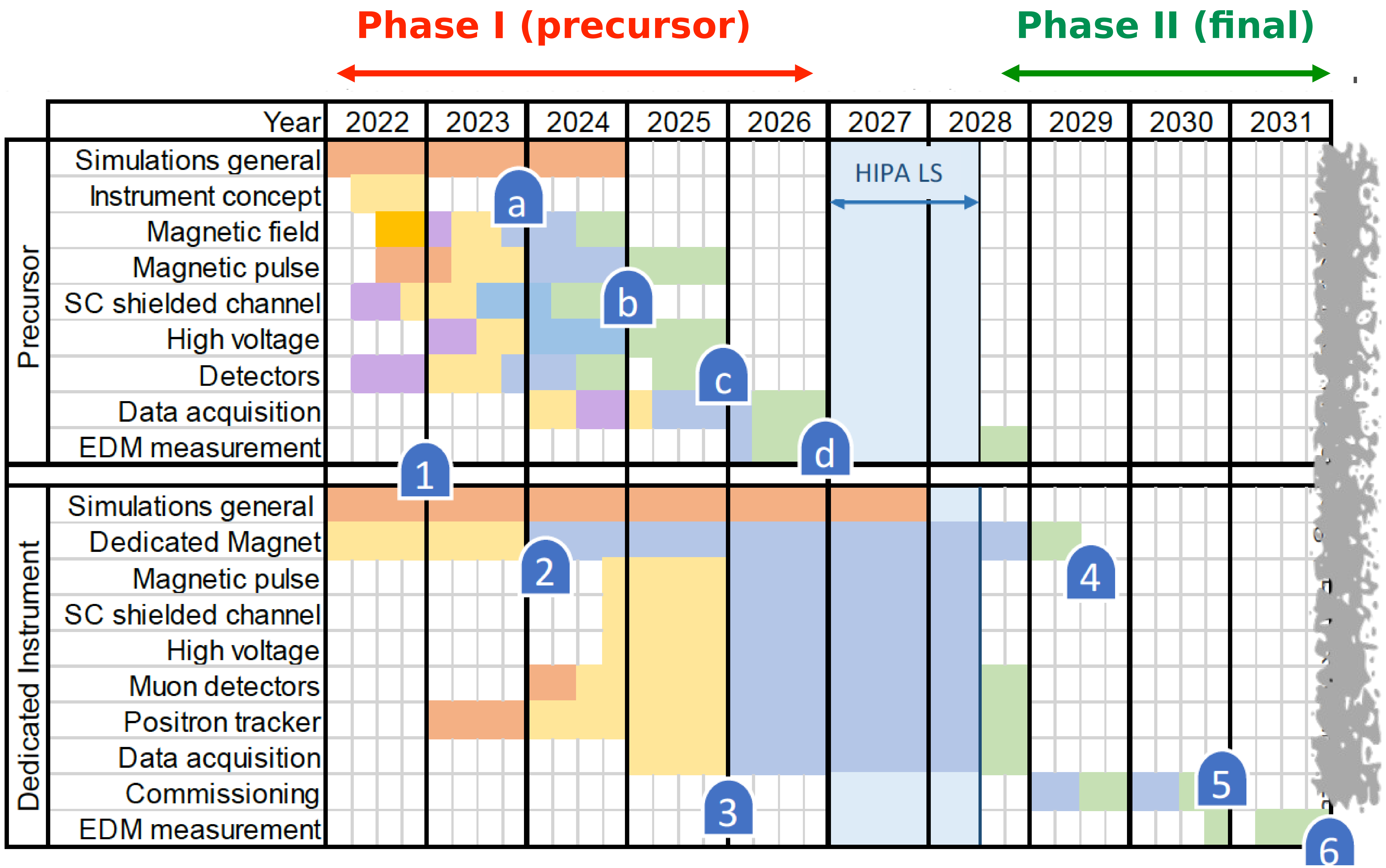
Demonstrate for the first time electric-field tuning to frozen-spin condition

First dedicated frozen-spin EDM measurement

A tentative schedule

Simulations
Conception/Design
Prototyping
Acquisition/Assembly
Tests/Measurements

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



High Intensity Muon Beam (HIBM) – approved

Ideas for experiments with HIBM

Science Case for the new High-Intensity Muon Beams HIMB at PSI

Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

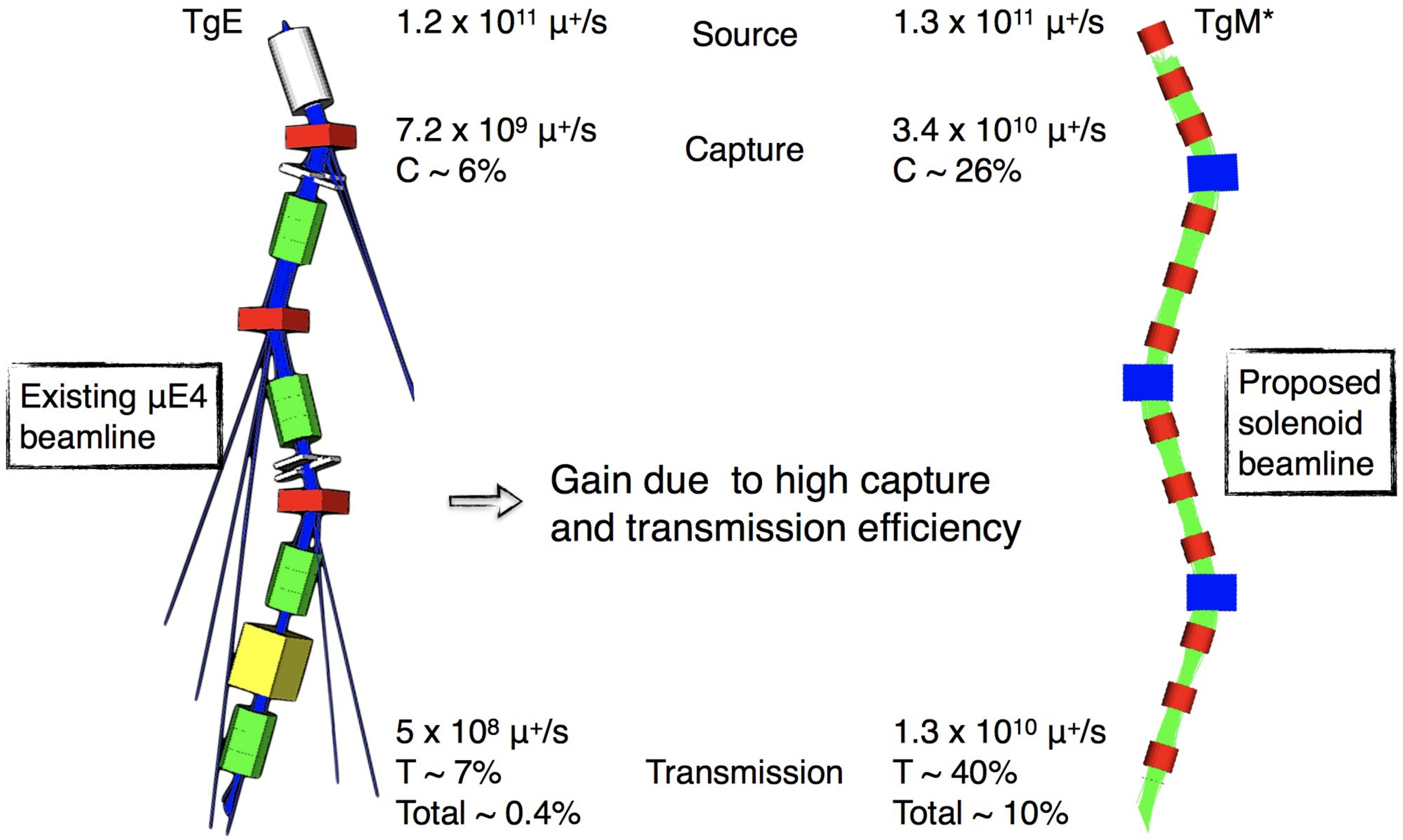
M. Aiba[1], A. Amato[1], A. Antognini[1,2], S. Ban[3], N. Berger[4], L. Caminada[1,5], R. Chislett[6], P. Crivelli[2], A. Crivellin[1,5], G. Dal Maso[1,2], S. Davidson[7], M. Hoferichter[8], R. Iwai[2], T. Iwamoto[3], K. Kirch[1,2], A. Knecht[1], U. Langenegger[1], A. M. Lombardi[9], H. Luetkens[1], F. Meier Aeschbacher[1], T. Mori[3], J. Nuber[1,2], W. Ootani[3], A. Papa[1,10], T. Prokscha[1], F. Renga[11], S. Ritt[1], M. Sakurai[2], Z. Salman[1], P. Schmidt-Wellenburg[1], A. Schöning[12], A. Signer[1,5,*], A. Soter[2], L. Stingelin[1], Y. Uchiyama[3], and F. Wauters[4]

[1]Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
[2]Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zürich, Switzerland
[3]ICEPP, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
[4]Institute for Nuclear Physics and PRISMA+ Cluster of Excellence, Johannes Gutenberg University Mainz, Germany
[5]Physik-Institut, Universität Zürich, 8057 Zürich, Switzerland
[6]Department of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom
[7]LUPM, Université de Montpellier, Place Eugène Bataillon, 34095 Montpellier, France
[8]Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
[9]CERN, 1211 Geneva 23, Switzerland
[10]Dipartimento di Fisica E. Fermi & INFN Sezione di Pisa, Largo Bruno Pontecorvo, Edificio C, 208, 56127 Pisa, Italy
[11]INFN Sezione di Roma, Piazzale A. Moro 2, 00185 Roma, Italy
[12]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
*Corresponding author: adrian.signer@psi.ch

In April 2021, scientists active in muon physics met to discuss and work out the physics case for the new High-Intensity Muon Beams (HIMB) project at PSI that could deliver of order $10^{10}\,\mathrm{s}^{-1}$ surface muons to experiments. Ideas and concrete proposals were further substantiated over the following months and assembled in the present document. The high intensities will allow for completely new experiments with considerable discovery potential and unique sensitivities. The physics case is outstanding and extremely rich, ranging from fundamental particle physics via chemistry to condensed matter research and applications in energy research and elemental analysis. In all these fields, HIMB will ensure that the facilities SμS and CHRISP on PSI's High Intensity Proton Accelerator complex HIPA remain world-leading, despite the competition of muon facilities elsewhere.

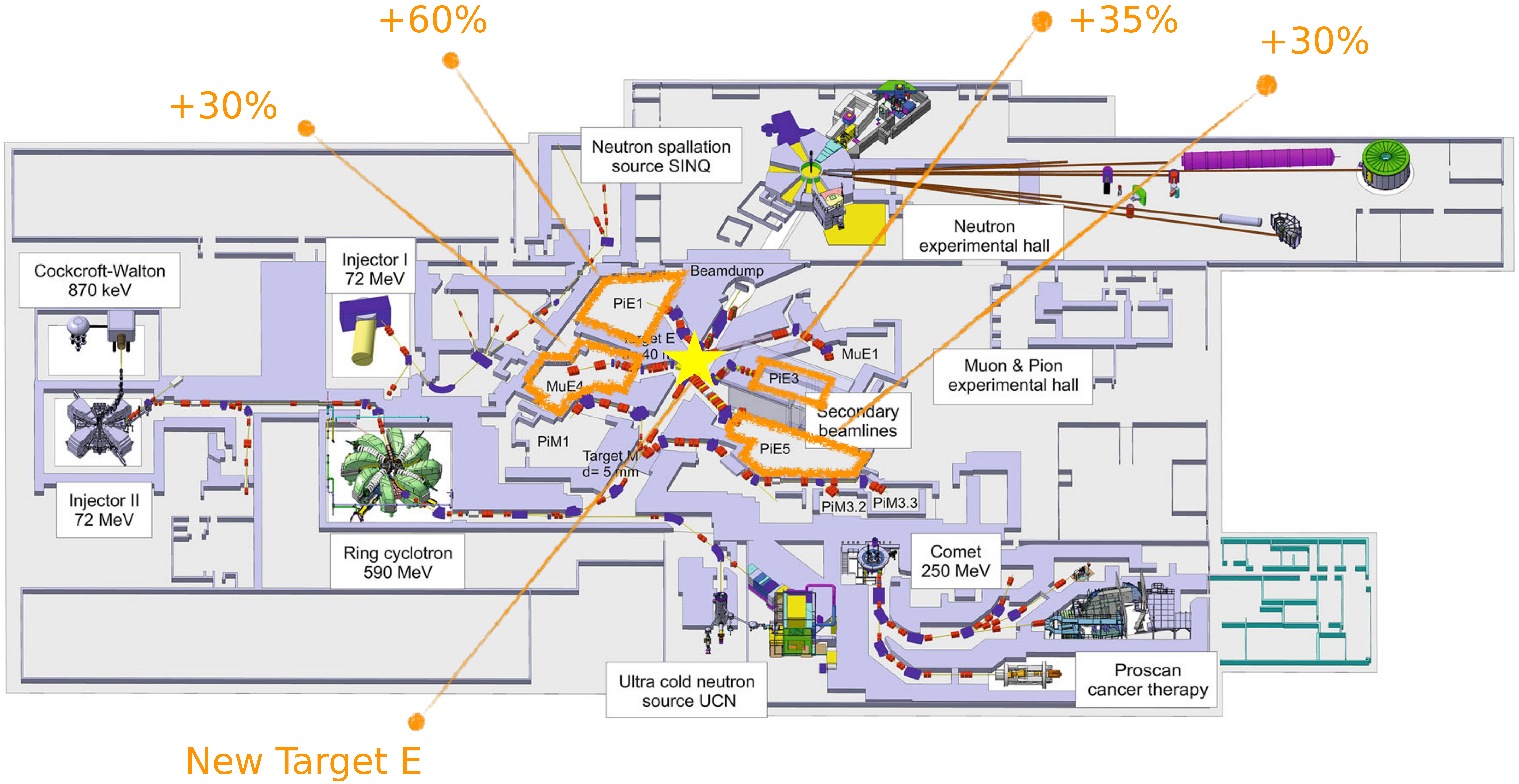
DC muon beams. Future prospects: HiMB

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: end **2028.** Long shut-down 2027-2028
- **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**



Ideas for HIMB

- $\mu \rightarrow eee$ (Mu3e experiment) phase II (already approved)
- g-2 of μ
  - Muonium source ($\mu^- e^+$) for spectroscopy, gravitational free fall and muonium-antimuonium oscillation
  - Muonic atom parity violation
  - $\mu \rightarrow e \gamma$ (MEGIII)

μ→eγ at HIMB: some ideas

– tracker based on thin silicon detector or radial TPC
- calorimeter based on fast high density crystal e.g. $LaBr_3(Ce)$
- alternatively Photon conversion spectrometer

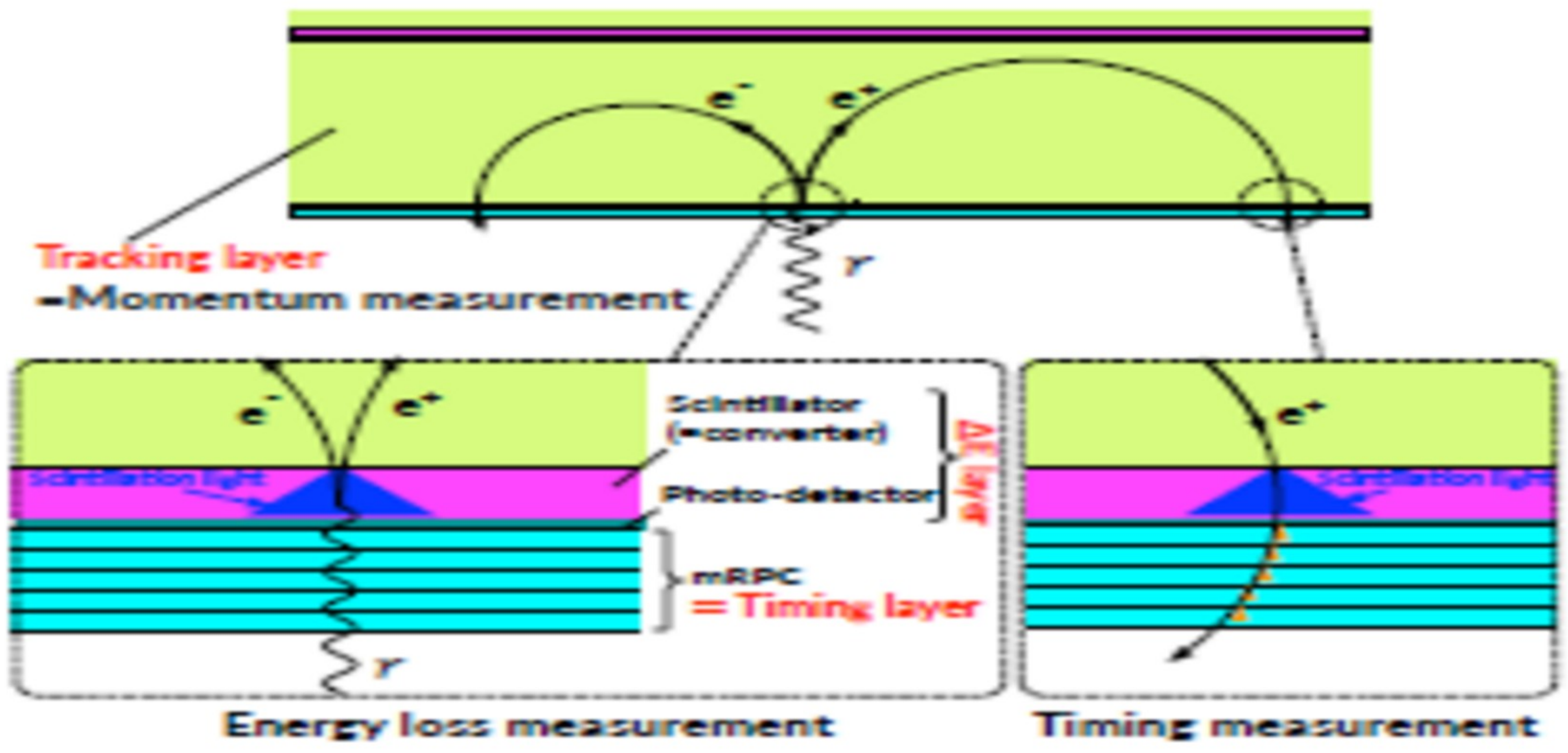


Figure 15: Possible structure of the active conversion spectrometer.

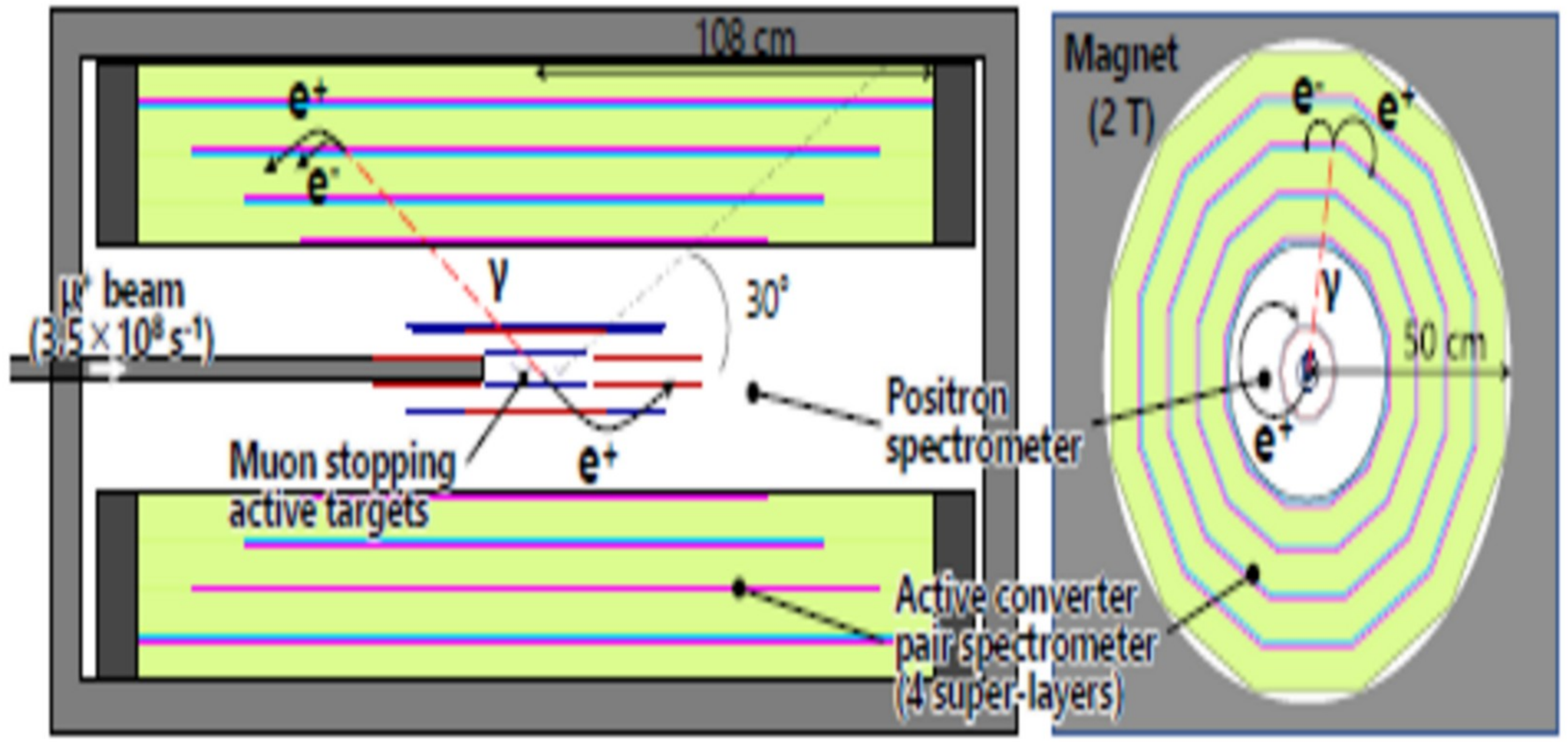


Figure 16: Possible layout of $\mu \to e\gamma$ experiment with photon conversion spectrometer.