PAUL SCHERRER INSTITUT PSI

MIP2024 @ PKU

Sensitive Search for the muon EDM with the Frozen-spin Technique

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on behalf of the *muEDM@PSI* collaboration

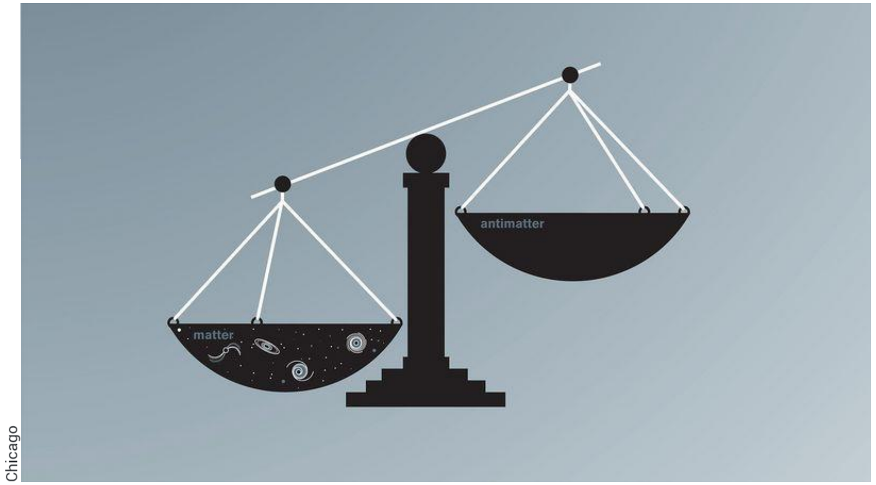
20th April 2024

李政道研究所
TSUNG-DAO LEE INSTITUTE

EDM is interesting to measure

Matter-antimatter asymmetry

Sakharov’s condition warrants more CPV



Credit: Symmetry Magazine / Sandbox Studio, Chicago

Fundamental particle with EDM violates CP

Violates T & P-symmetry, and by invoking CPT invariance violates CP

https://edm.ethz.ch/research/nedm.html

$$\boxed{\mathrm{H} = -\mu\hat{\mathrm{s}}\cdot\overrightarrow{\mathrm{B}} - \mathrm{d}\hat{\mathrm{s}}\cdot\overrightarrow{\mathrm{E}}}$$

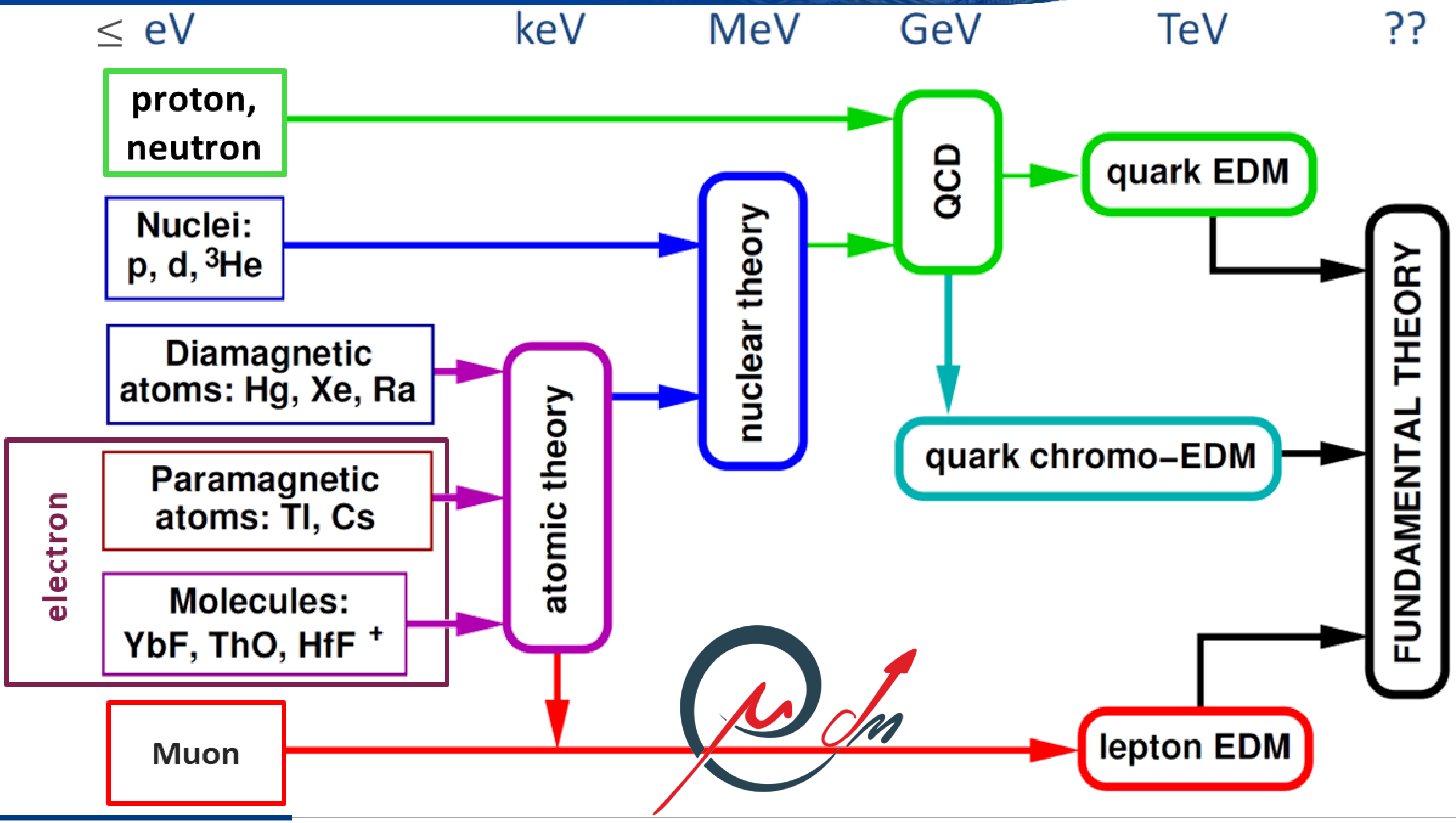
- **Free from SM backgrounds**
  - CKM phase contribution: $d_\mu \sim 10^{-42}\ e\cdot cm$
  - Hadronic long distance contribution: $d_\mu \sim 10^{-38}\ e\cdot cm$ [2]

PRD **89** (2014) 056006

PRL **125** (2020) 241802

- **Various BSM models and EFT approaches predicts enhanced EDM**
  - EDMs are good probes for BSM physics

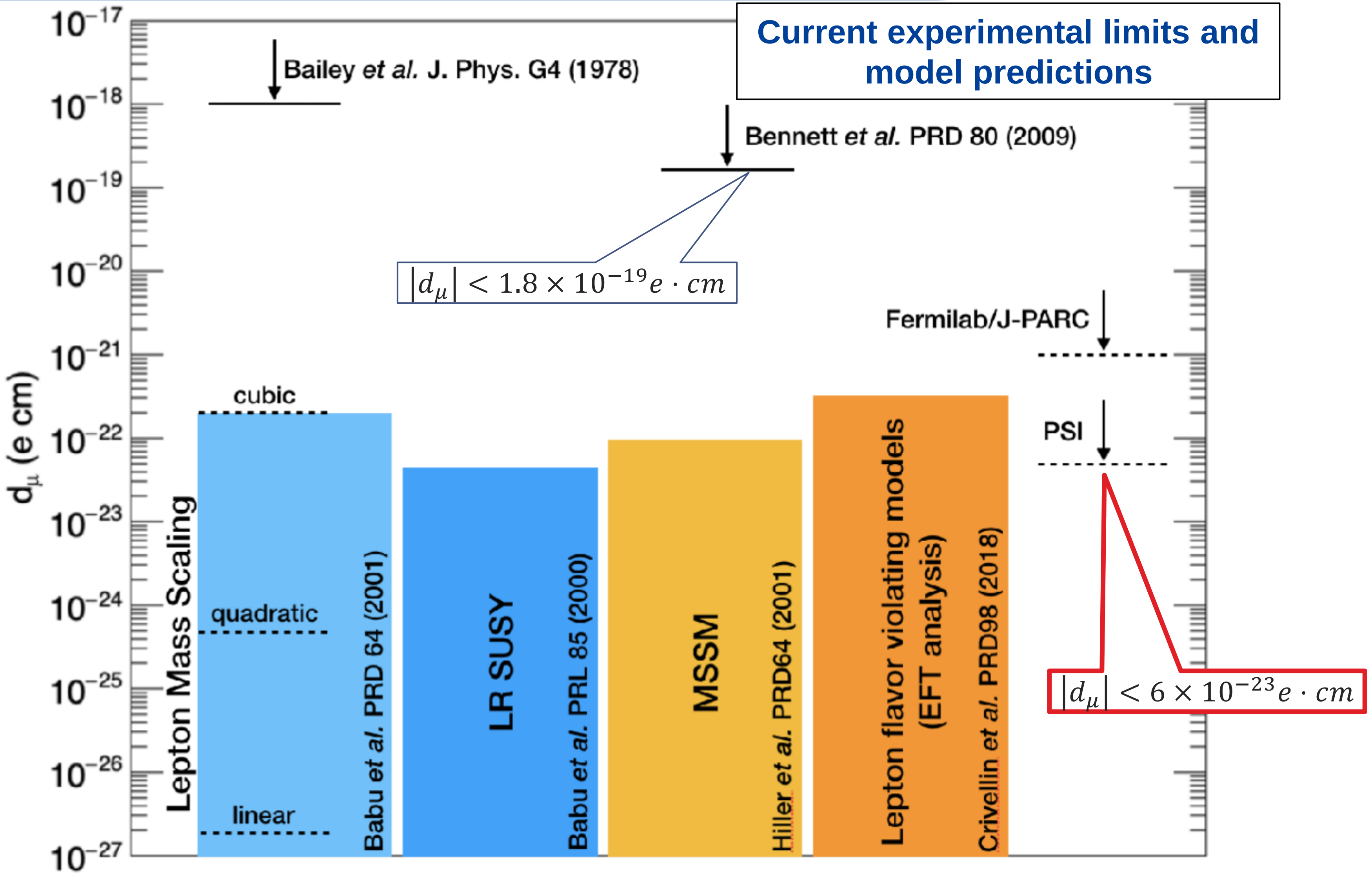
Many EDMs, why muon?



Scheme: adapted from Rob G.E.Timmermans and PSW

Present Landscape of μEDM

Current experimental limits and model predictions

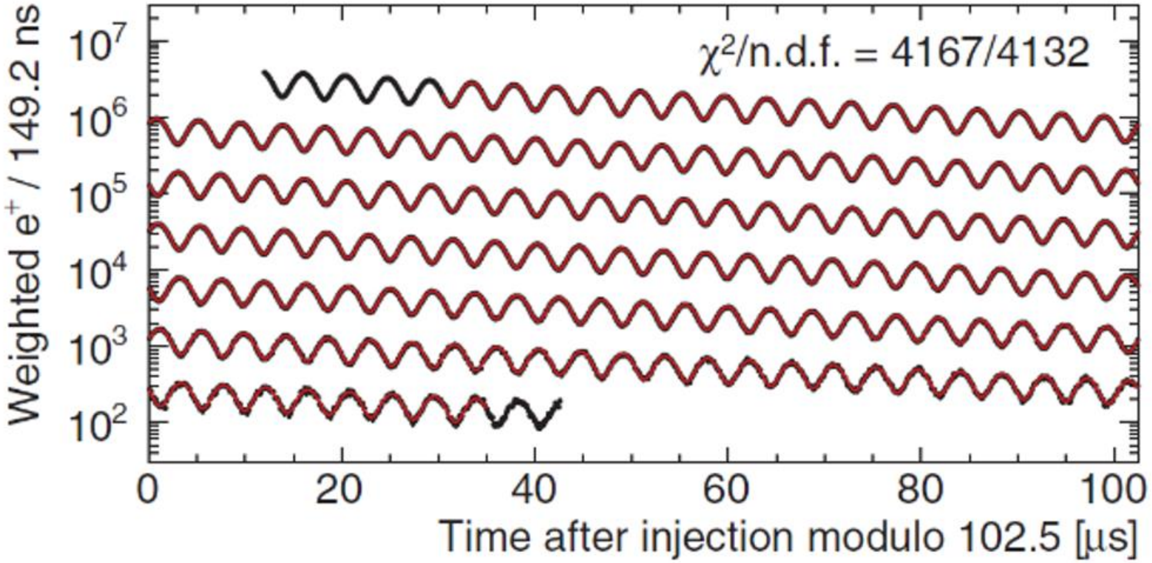


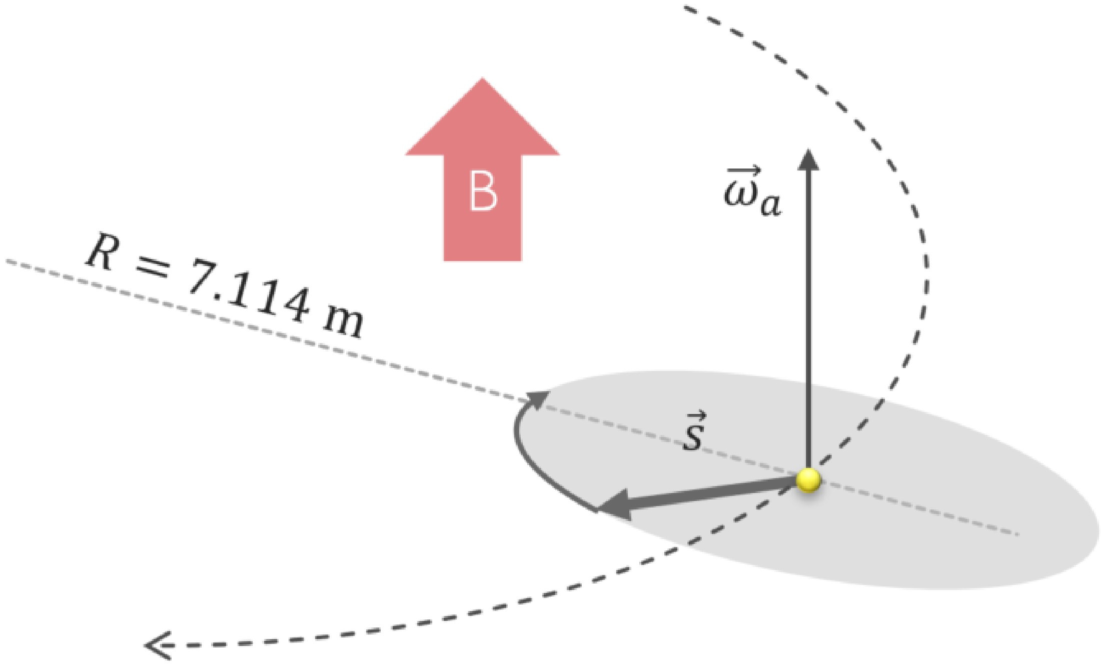
K.S. Khaw @ NuFACT 2022

Measuring μEDM

Tsung-Dao Lee Institute

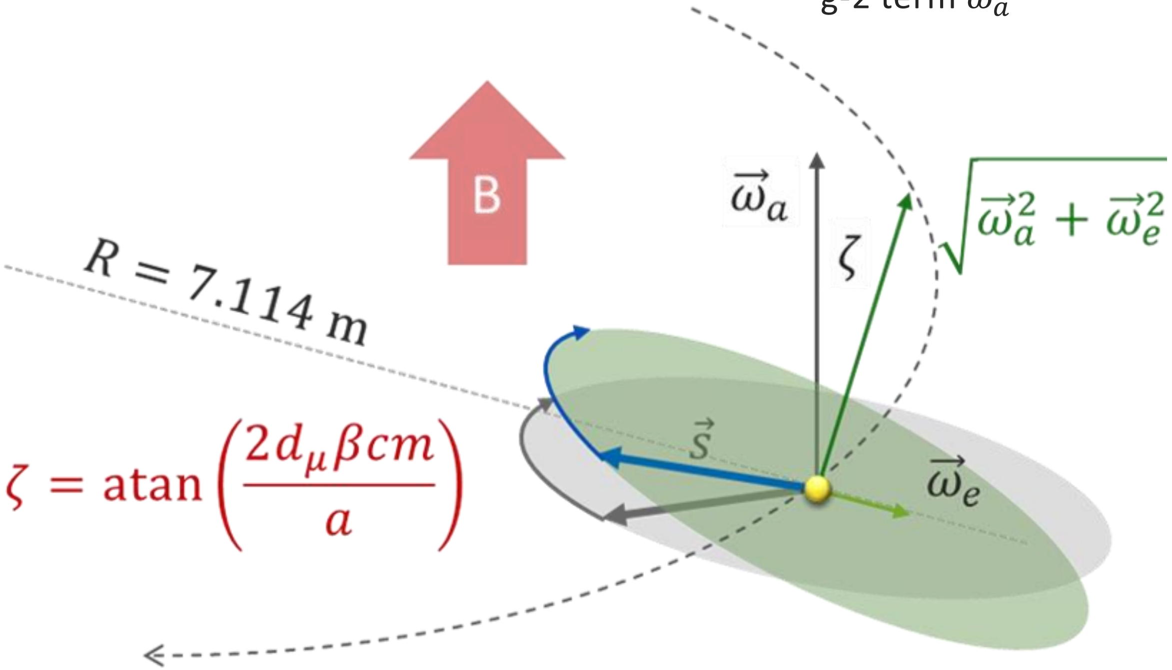
$$\vec{\omega} = \vec{\omega}_L - \vec{\omega}_c = -\frac{q}{m}\Bigg[\underbrace{a\vec{B} + \cancel{\left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2 term } \omega_a}\Bigg]$$



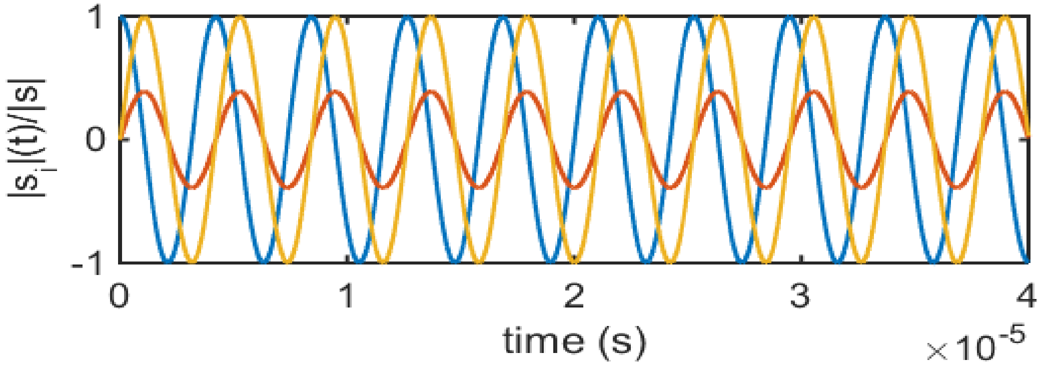


Measuring μEDM

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



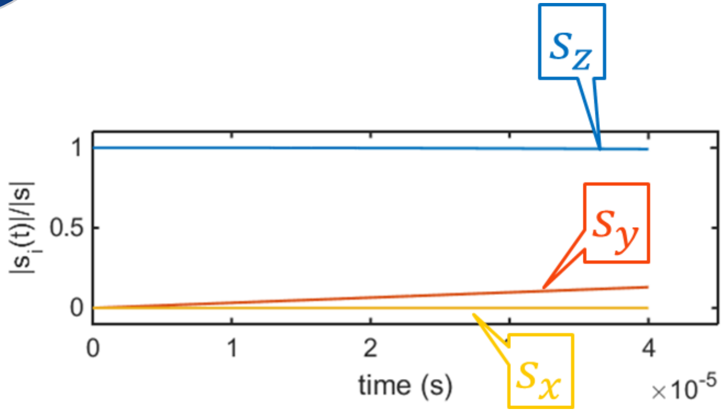
$\zeta \sim \mathrm{mrad}$ for $d_\mu \sim 10^{-19}\ e\cdot em$: Such small angle is challenging for high precision measurement



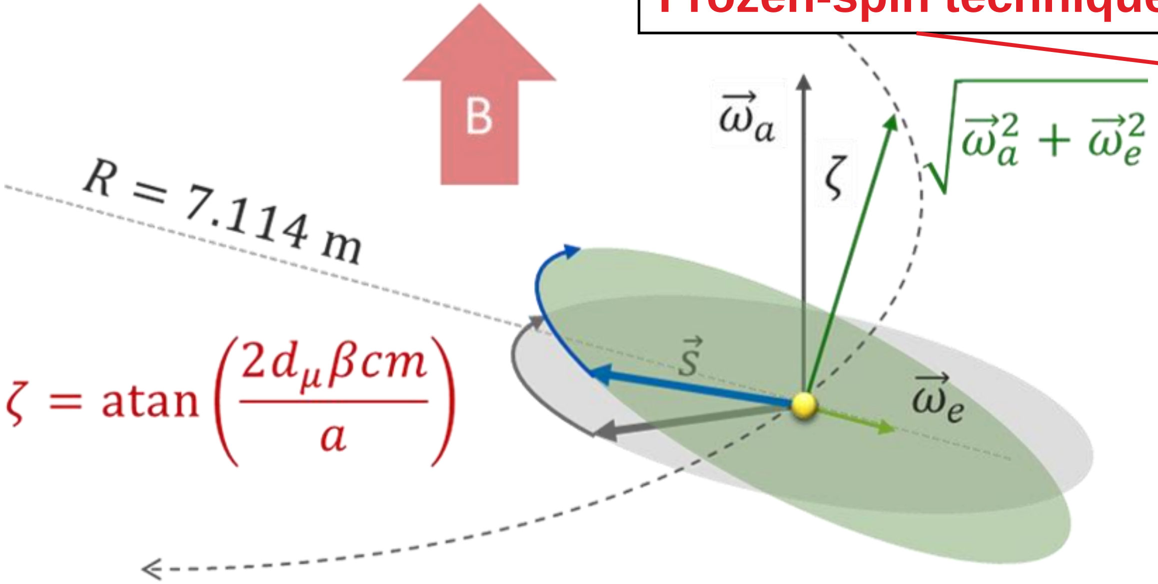
Prospected sensitivities at FNAL and JPARC,
$\boldsymbol{\sigma(d_\mu) \approx 10^{-21} ecm}$

Measuring μEDM at PSI

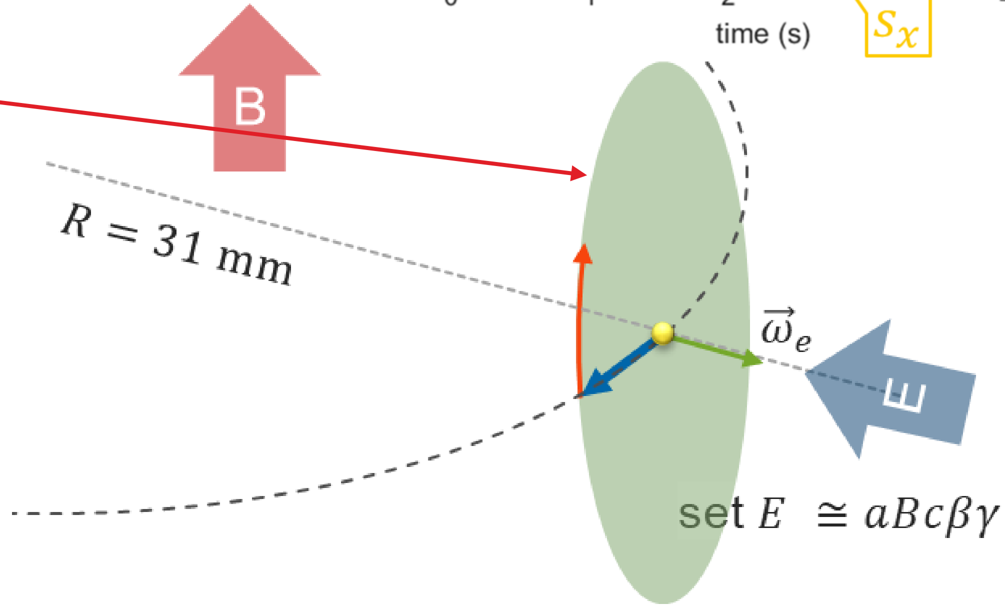
$$\vec{\omega} = -\frac{q}{m}\Bigg[\underbrace{\cancel{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2 term } \omega_a} + \underbrace{\frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM term } \omega_e}\Bigg]$$



Frozen-spin technique



$$\zeta = \operatorname{atan}\left(\frac{2d_\mu \beta cm}{a}\right)$$

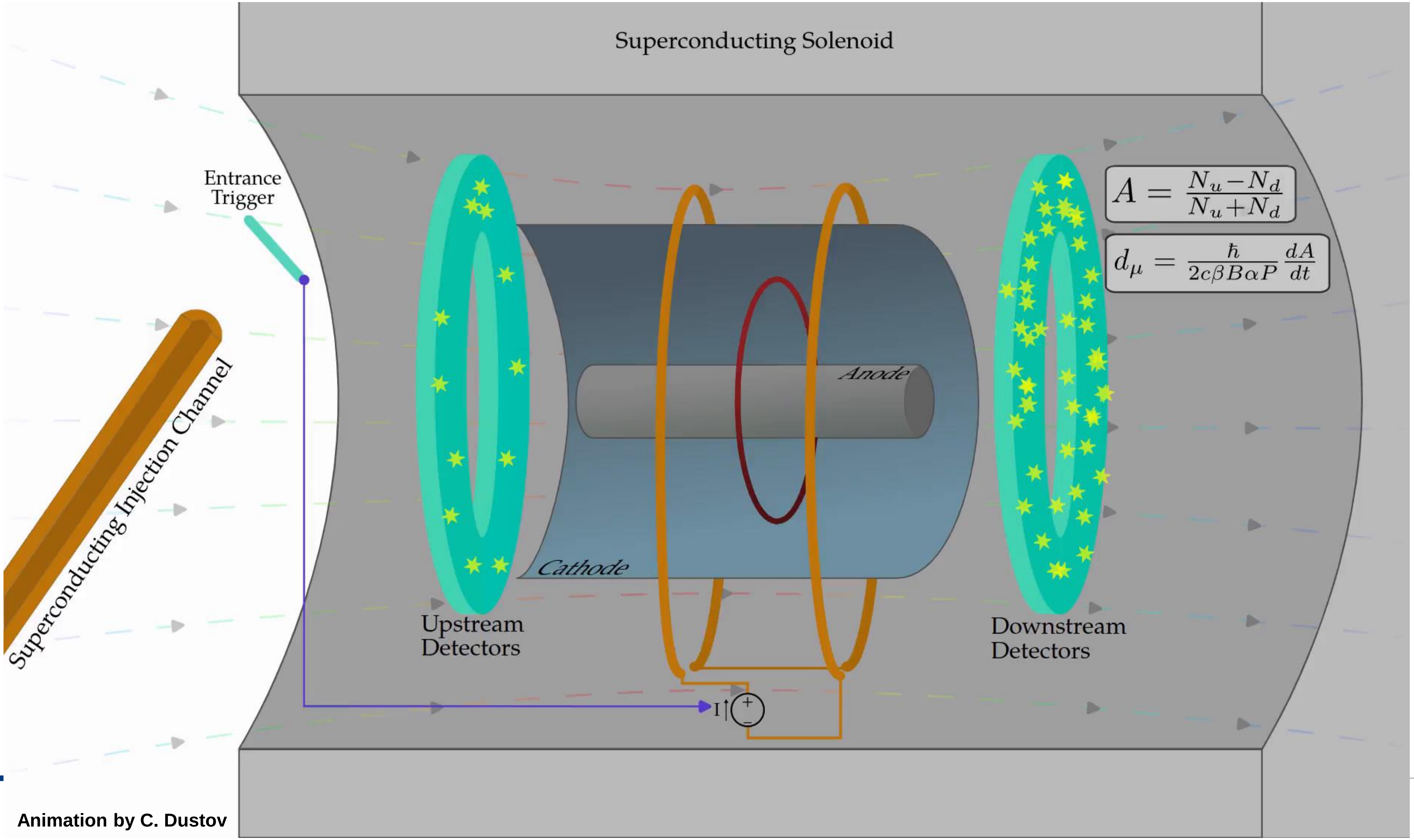


set $E \cong aBc\beta\gamma^2$

$\zeta \sim$mrad
for $d_\mu \sim 10^{-19} e \cdot em$: Such small angle is challenging for high precision measurement

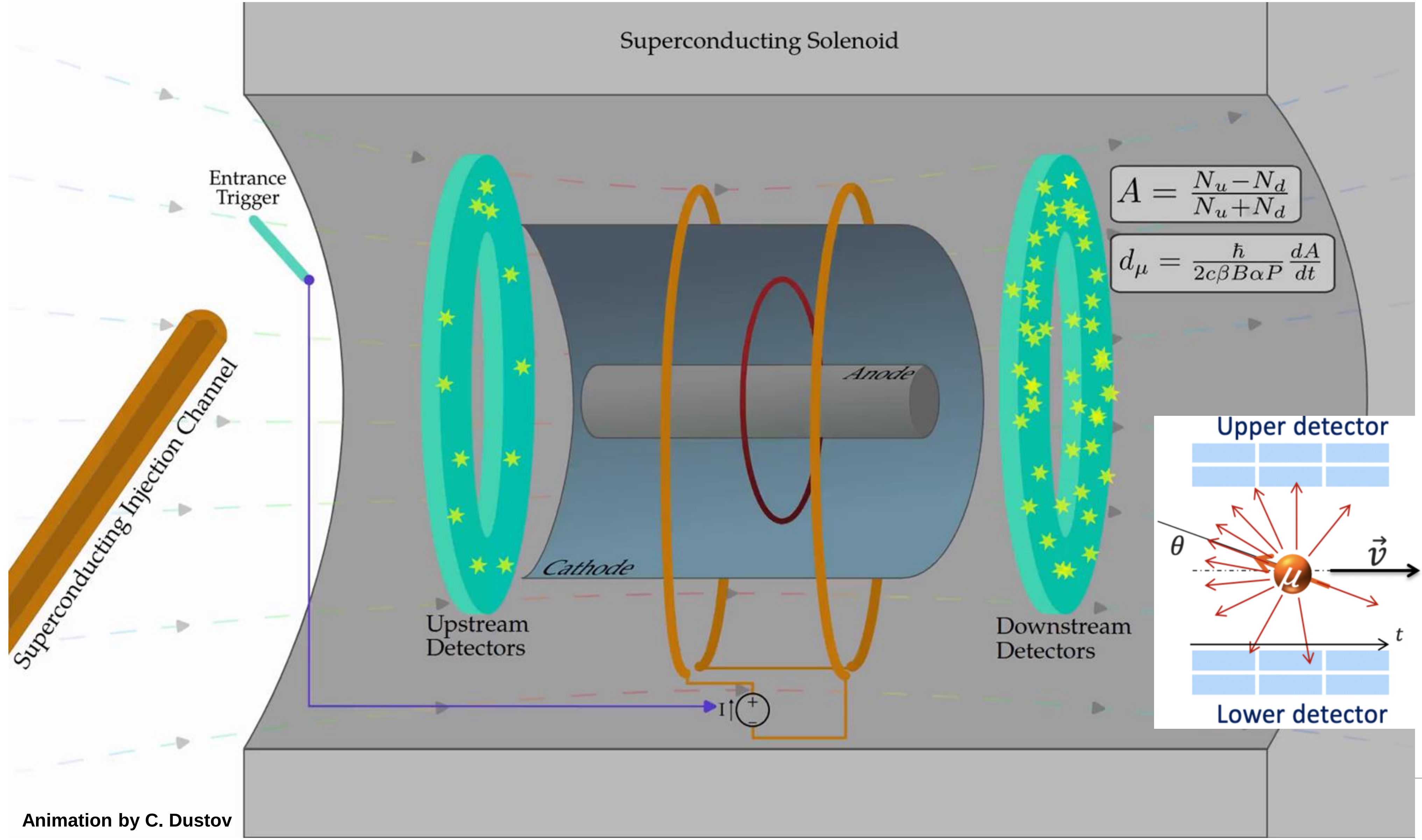
- Cancels g-2 precession, purely measuring EDM precession
- Spin freezes in direction of momentum if no EDM

Experiment Layout



Animation by C. Dustov

muEDM Signal



Animation by C. Dustov

Sensitivity from the asymmetry, "PENTA":

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

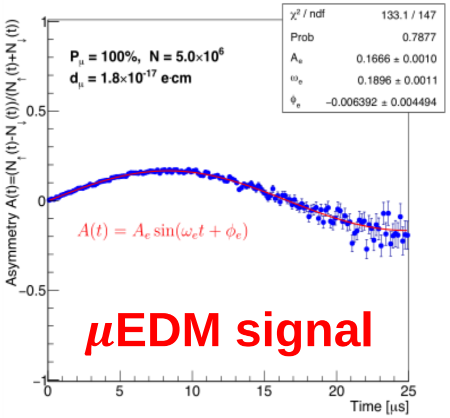
P := initial polarization

E_f := Electric field in lab

$\sqrt{N}$:= number of positrons

τ_μ := lifetime of muon

α := mean decay asymmetry



Phased Approach

	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.017	0.60
Muon storage rate (1/s)	2×10^3	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	500	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.3	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year (e·cm)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

muEDM proposal

Phase-I

- Surface muons, p = *28 MeV/c*
- Existing, smaller solenoid at PSI (Bore diameter = 200 mm)
- $d_\mu = 3 \times 10^{-21}\ e \cdot cm$ by 2026

Phase-II

- Higher momentum muons, p = *125 MeV/c*
- Dedicated solenoid (Bore diameter = 900 mm)
- $d_\mu = 6 \times 10^{-23}\ e \cdot cm$ by 2031

muEDM Phase-I

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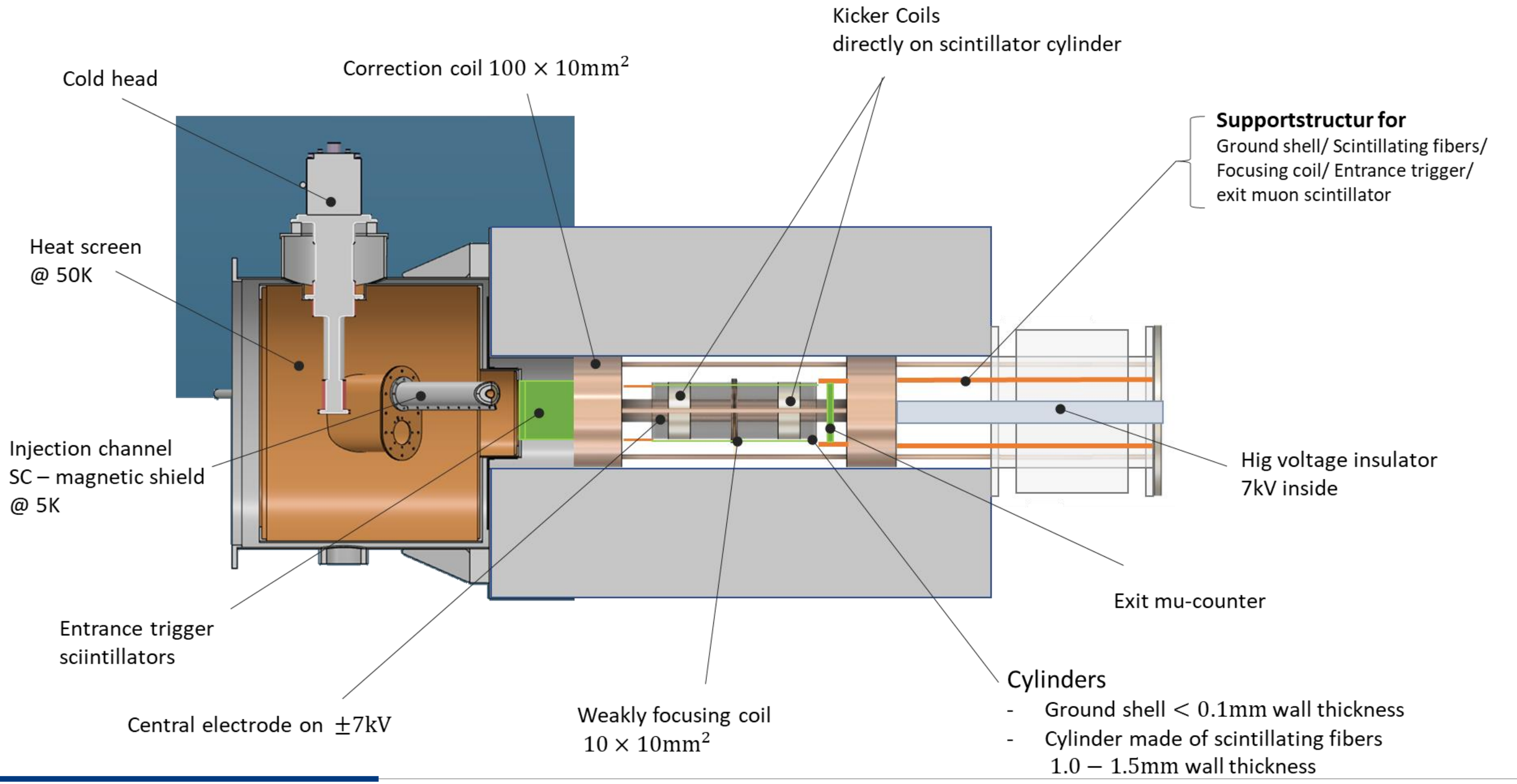
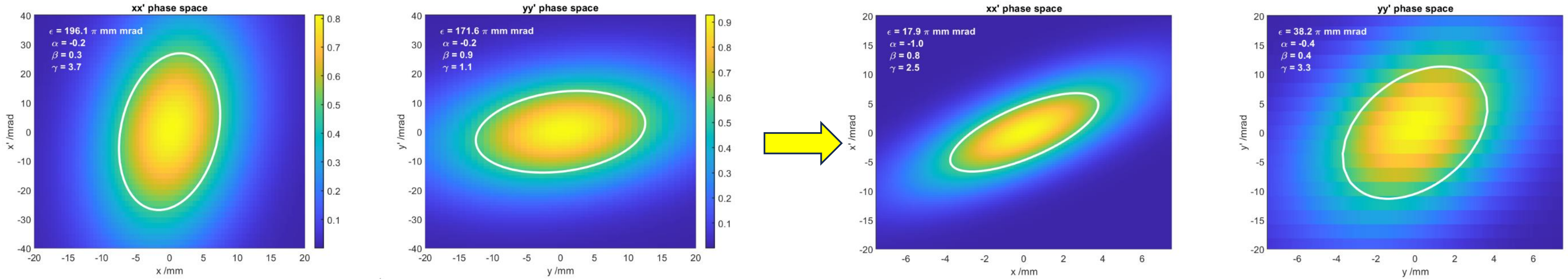


Muon Injection



- **Large phase space at exit of beam collimated by passage through a collimation channel**
- **Surrogate models along with G4BL to optimize injection**
- **Storage efficiency** $\sim \mathbf{0.5 \times 10^{-4}}$
- **Superconducting channels to shield fringe field from storage solenoid**

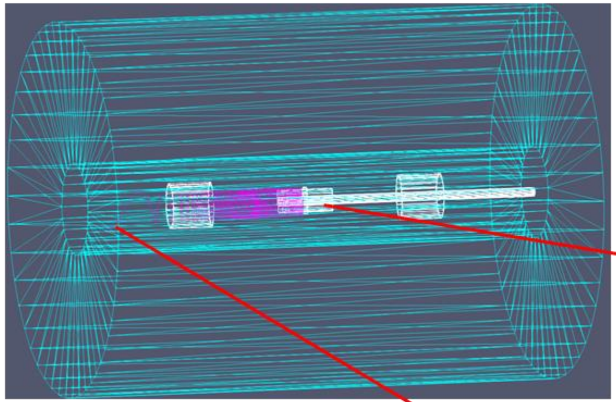
Details from Yuzhi's poster

Muon Entrance Detector

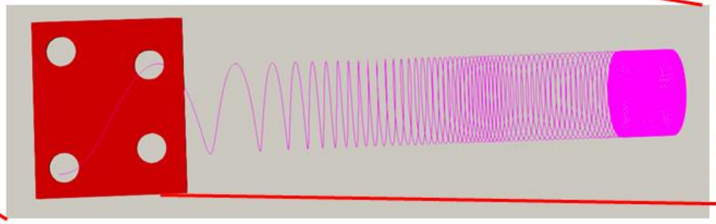
- **Fast entrance detector to trigger magnetic pulse kicker**
  - Selects muons within storage acceptance phase space
  - Sends fast signal without causing notable multiple scattering

Requirements and challenges

- **Thin scintillators (50 μm to 100 μm) to minimise multiple scattering effect**
  - Low number of photons to trigger pulse kicker
- **Timing requirements**
  - Time delay between trigger and pulse kick, $t_{delay} < 150ns$

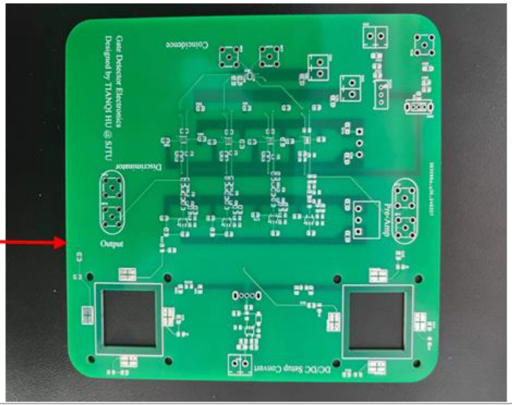


Muon injection and storage optimisation



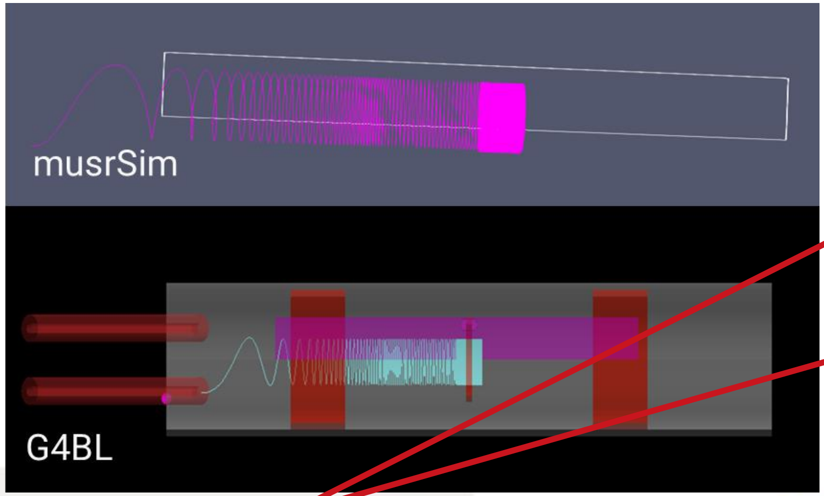
Entrance detector design and optimisation

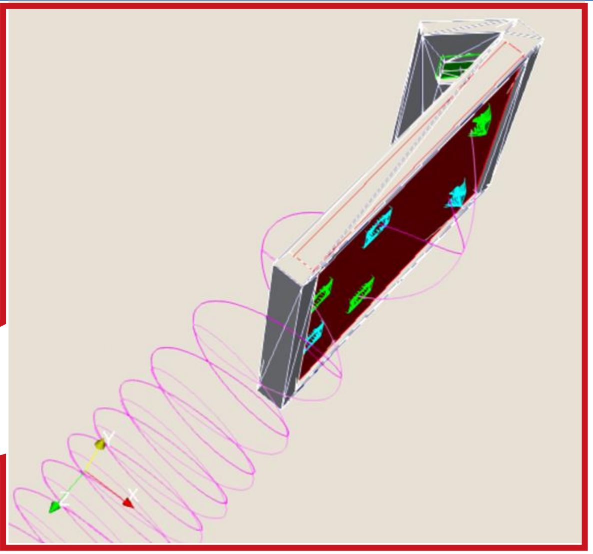
Fast electronics development



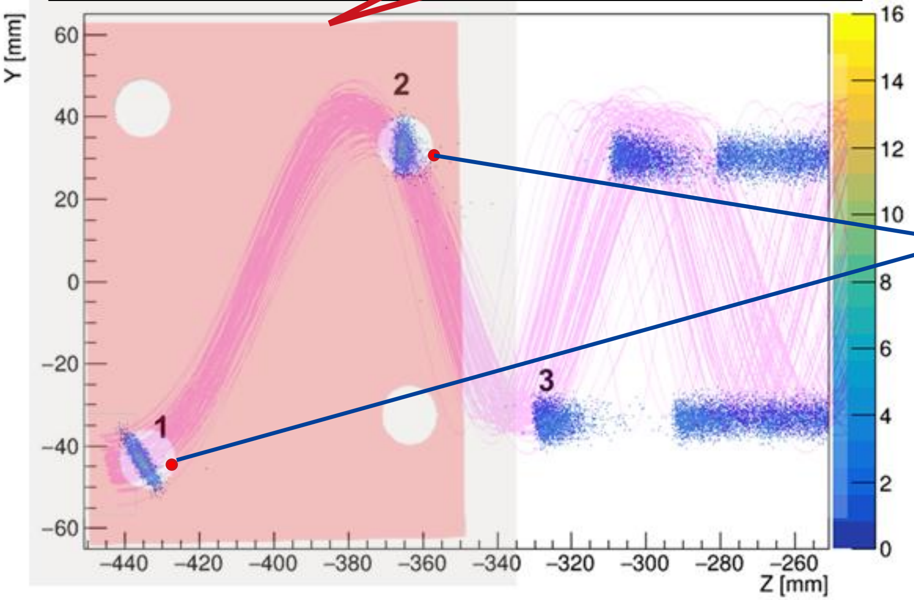
Muon Entrance Detector

Geometry baselined with nominal storage muon trajectory





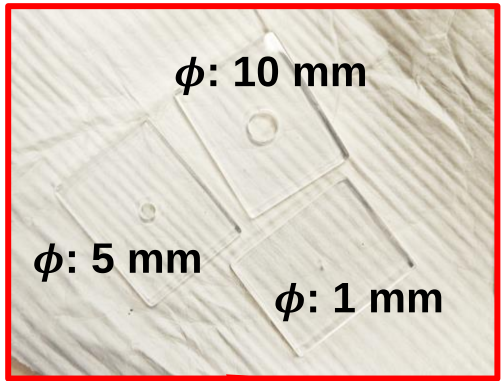
Hit positions on active aperture

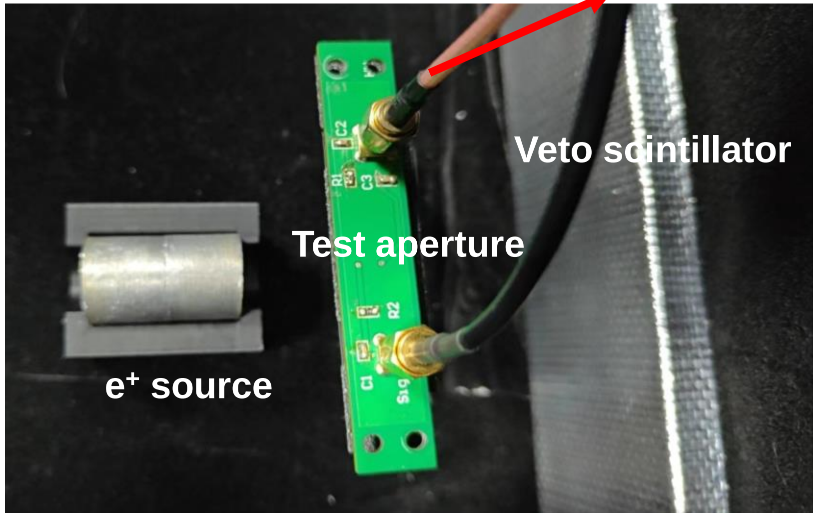


Muon's within storage phase space acceptance selected with *aperture* scintillator

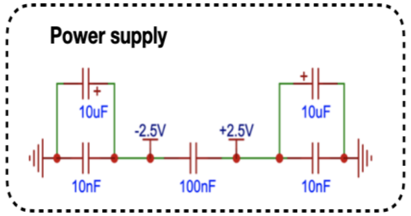
Entrance detector test bench

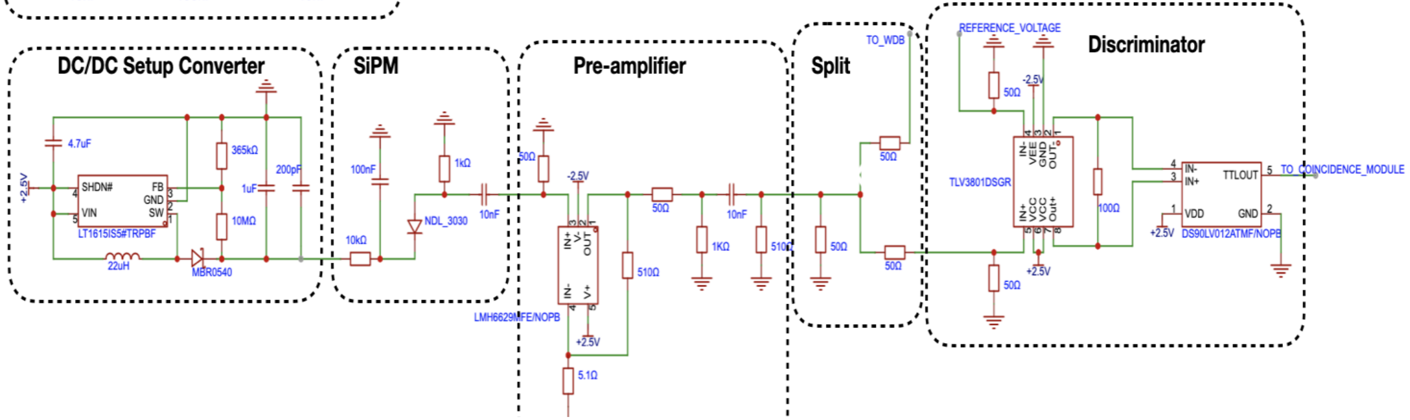
- Event rates of various aperture geometries and dimensions studied
- Establish a feedback loop between test bench and simulation
- e^+ "pencil beam" + *B-field + vacuum chamber*



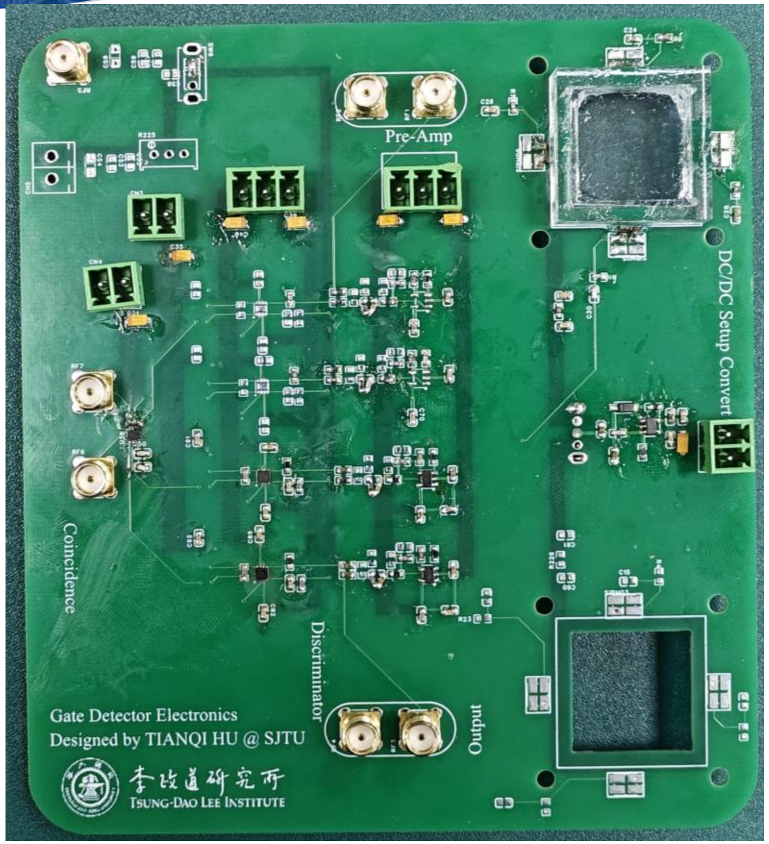


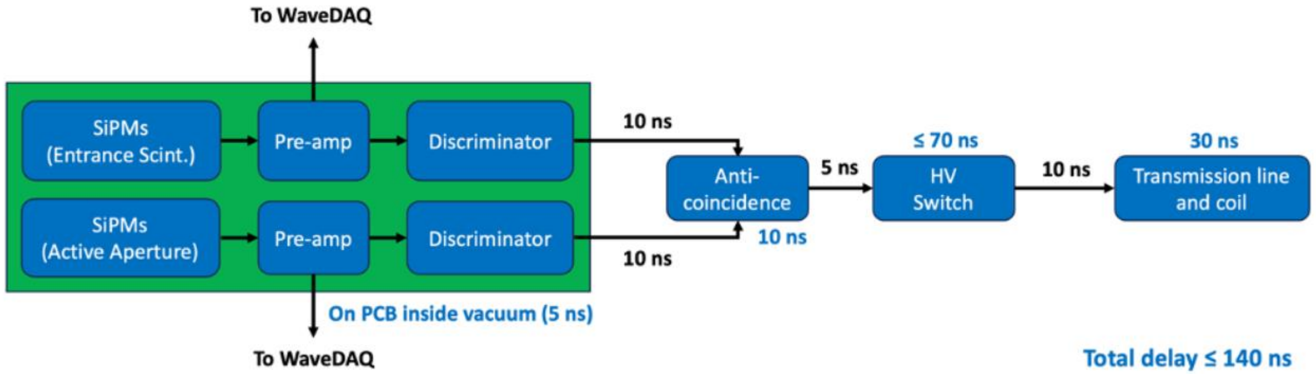
Muon Entrance Detector





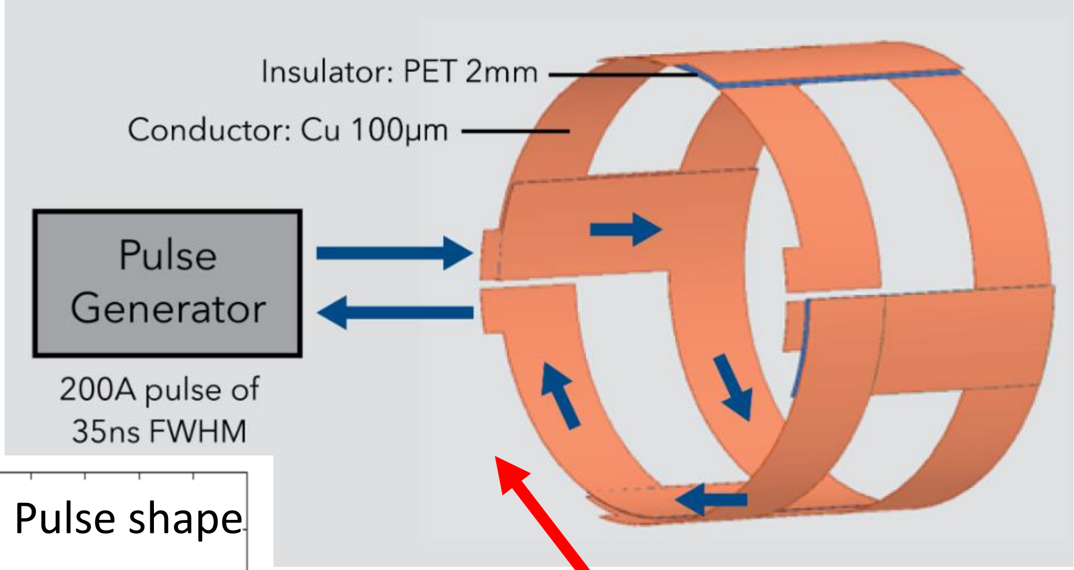
Details from Tianqi's poster

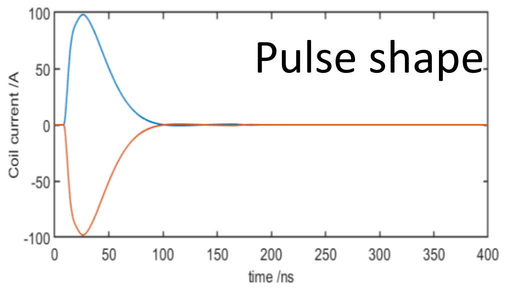


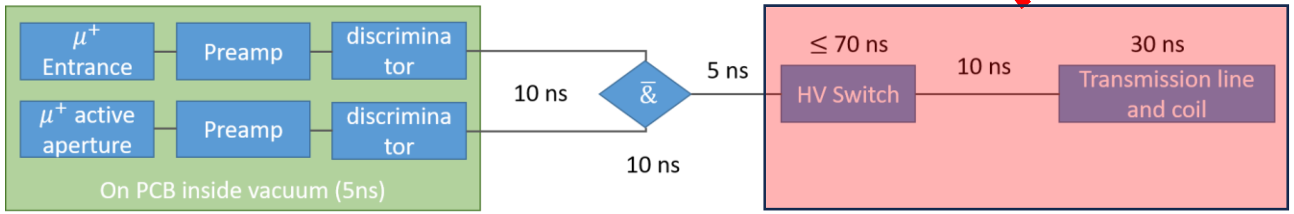


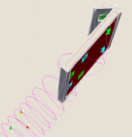
- **Prototype fast electronics were designed and tested**
- **Propagation delay was evaluated at no more than 5 ns**

Storage Pulse Kicker



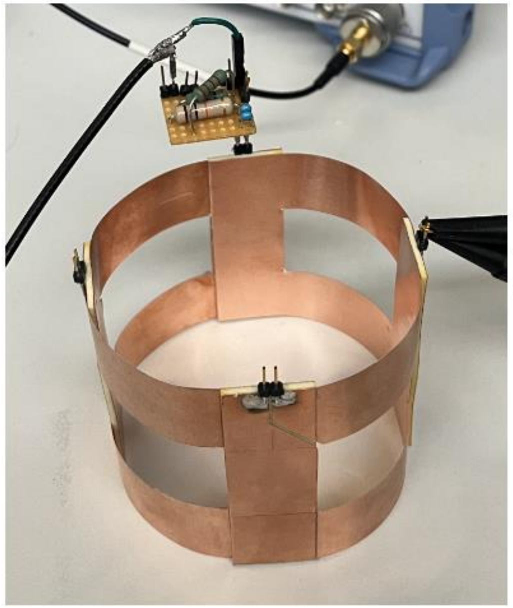


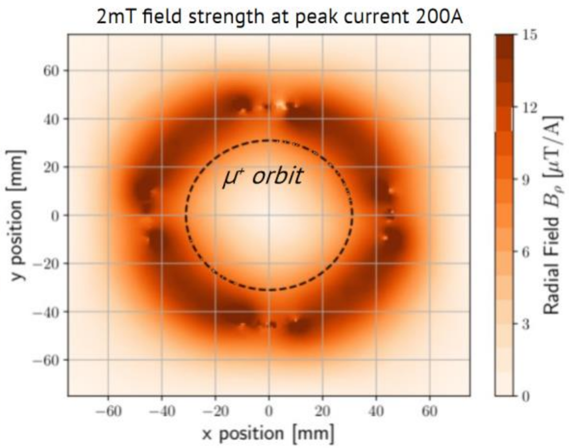




Short trigger delay necessitates internal latency of pulse generator to < *60 ns*

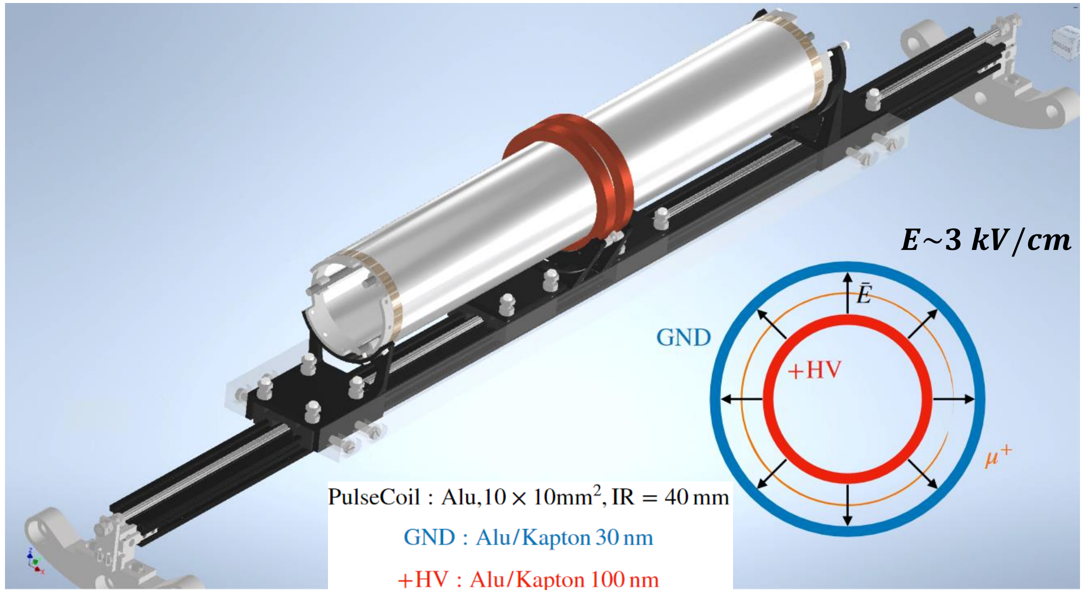
First prototype





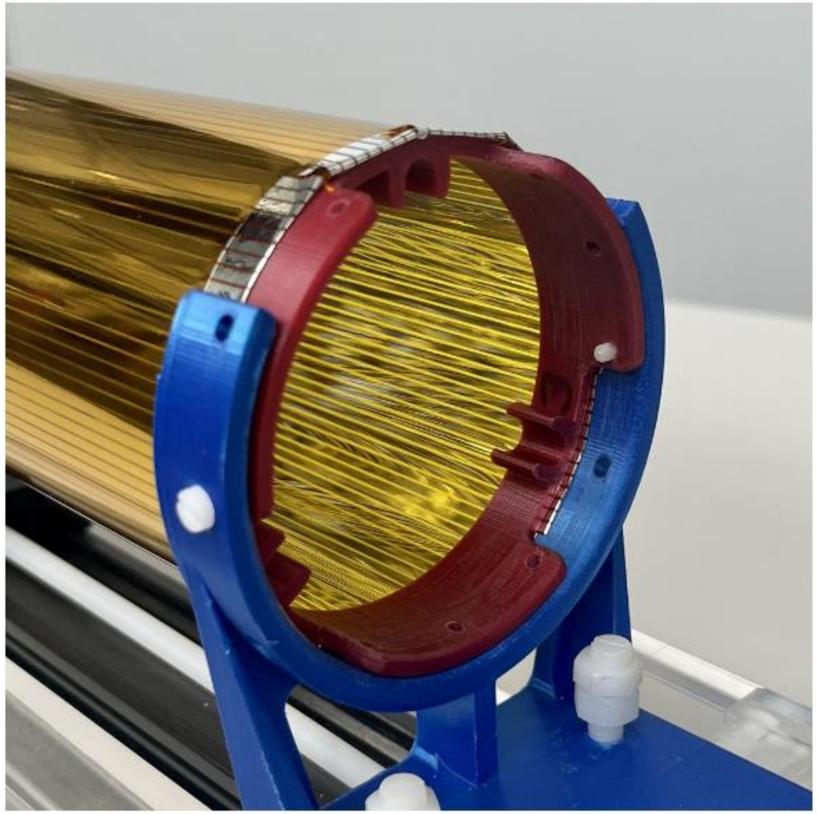
- **Coil quadrants generating pulsed longitudinal kick to store muons**
- **Technical requirements:** High amplitude, rapid triggering of short duration pulsed magnetic field, with strong tail suppression

Frozen-spin Electric Field



- **Radial electric field applied by two concentric electrodes enclosing muon orbit**
- **Technical requirements:**
  - Precise alignment with muon storage plane
  - Heat dissipation
  - Minimal multiple scattering

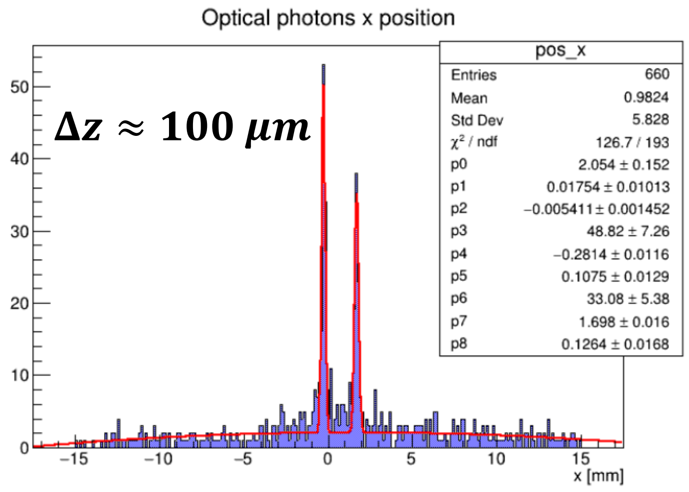
Current approach:
- 25μm Kapton films
- Strip-segmented ~30nm Al coating
- 2mm thickness
- 2.2mm pitch

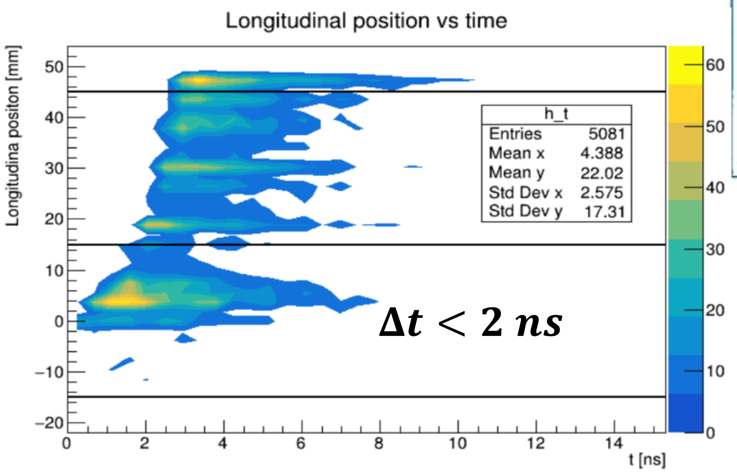


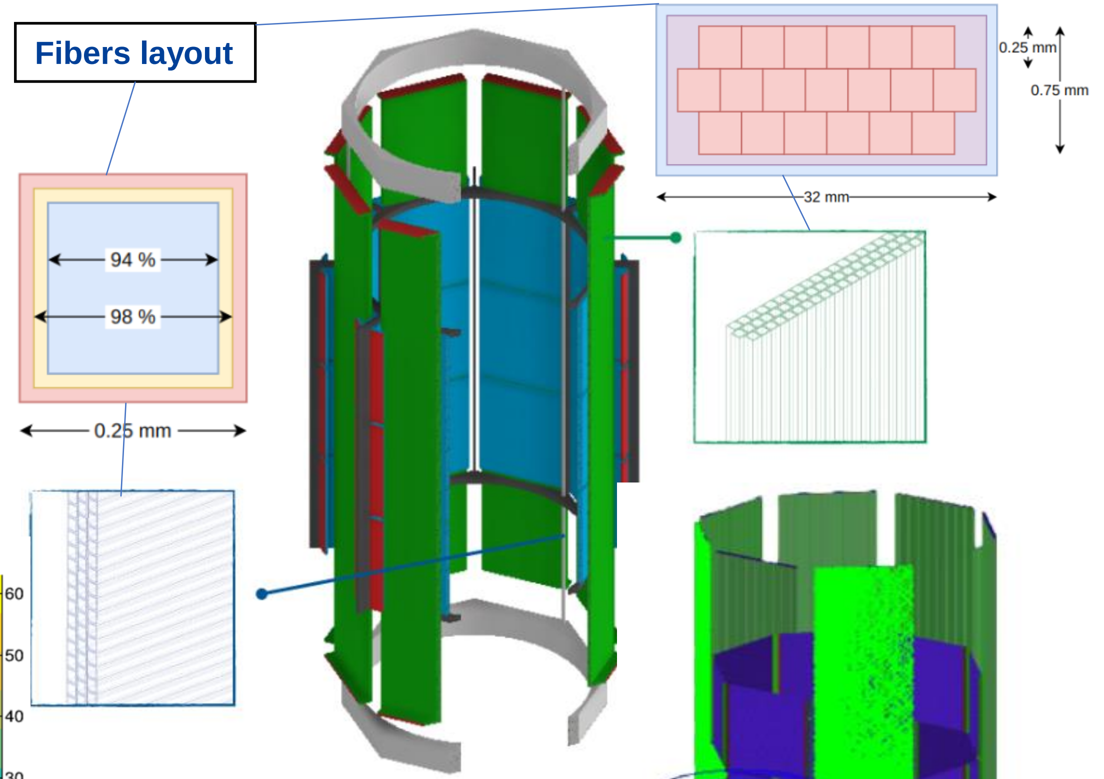
Strip-segmented AluKapton film approach ***suppresses Eddy current damping****, without compromising* ***electric field uniformity****.*

Positron Detection: EDM Signal

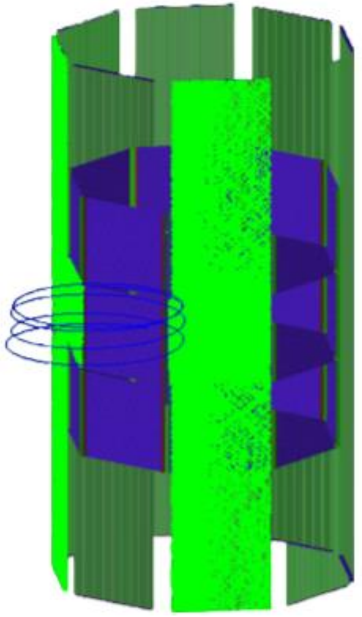
- **Double barrel Scifi tracker**
- **Measures longitudinal asymmetry of positron**
- **Bundles of fibers with good resolution**
  - transverse and longitudinal fibers
  - transverse fibers with longitudinal straw/pix





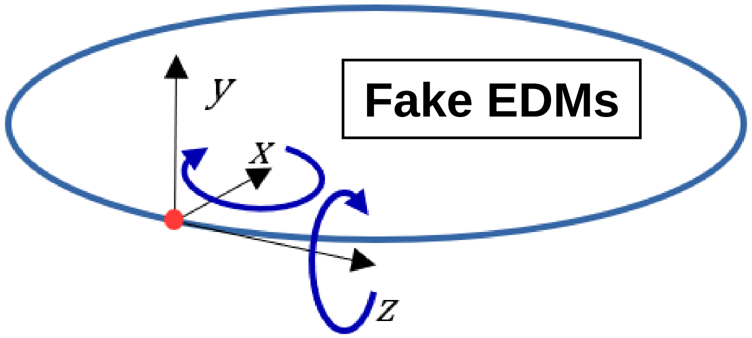


- Photon time and position (longitudinal info on internal barrel)
- Large number of readout channel a challenge
- Considering other possible geometries



Potential Systematic Effects

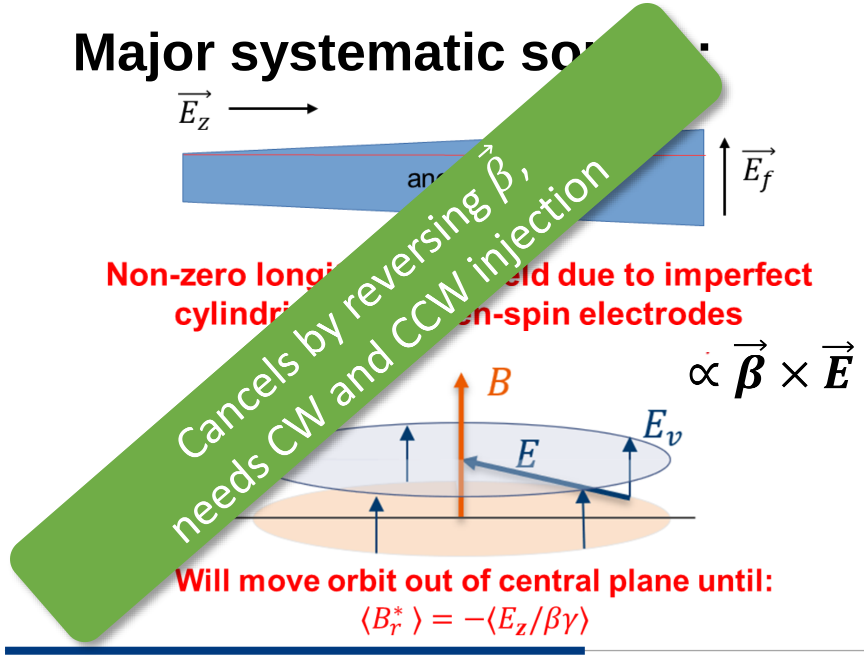
Real or apparent precessions mimicking the EDM signal



- **Real:** MDM coupling to EM fields of experimental setup
- **Apparent:** Variation in detection efficiency

Systematics carefully studied with Geant4 spin tracking simulations

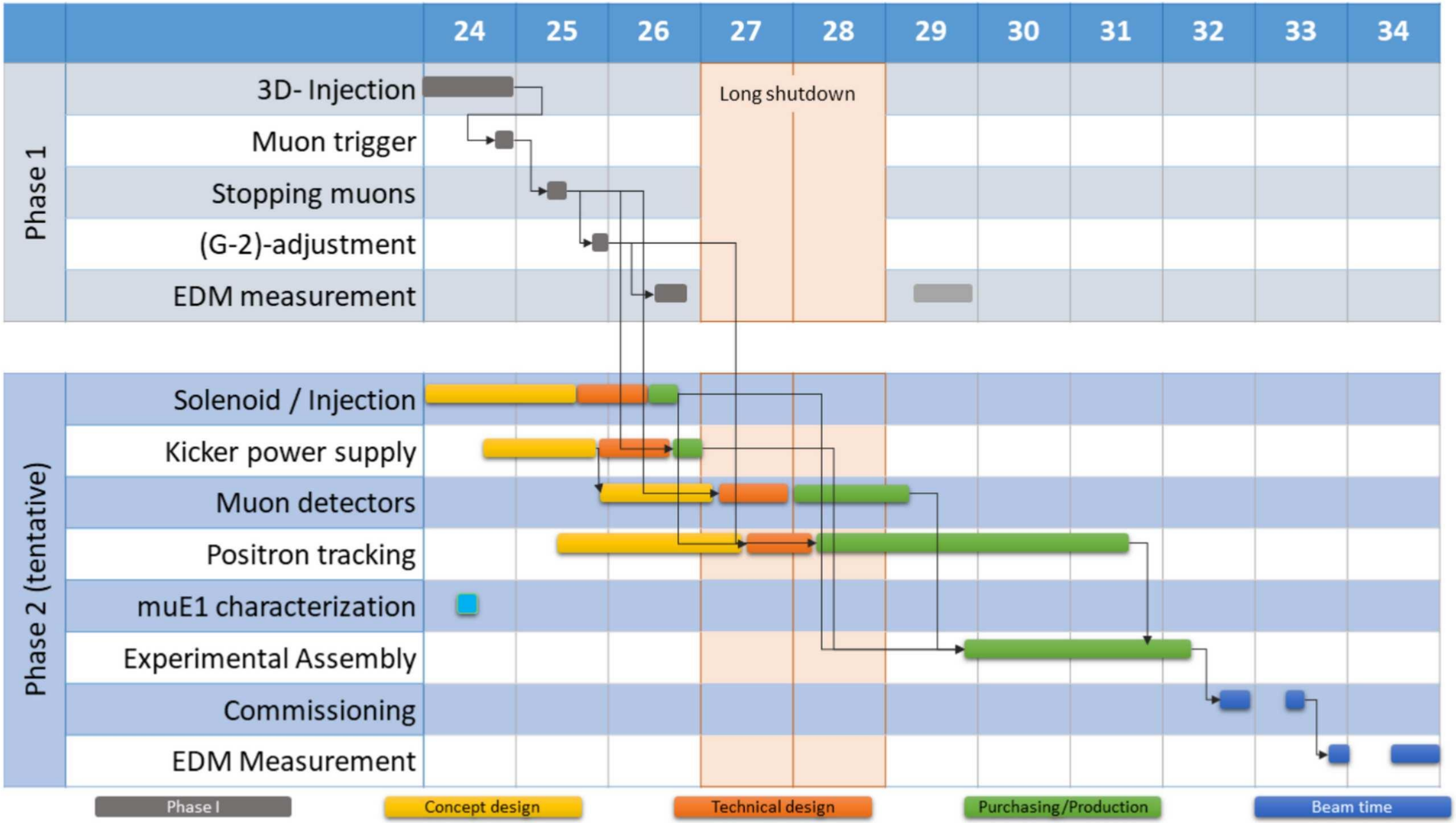
Systematic effect	Constraints	Phase I	
		Expected value	Syst. ($\times 10^{-21}$ e·cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ μm	0.75
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$
Net current flowing muon orbit area	Wiring of electronics inside the orbit	< 10 mA	$< 10^{-2}$
Longitudinal B-field uniformity	Solenoid alignment	< 3 mT	-
Resonant geometrical phase accumulation	Misalignment of central axes	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}
TOTAL			1.1



Summary

- μEDM is a strong probe for BSM new physics that complements high energy experimental efforts
- A dedicated, sensitive search for a μEDM is under development at PSI
- Expect three orders of improvement in sensitivity from current best limit
  - Phase I: $d_\mu < 3 \times 10^{-21}\ e \cdot cm$ ~2026
  - Phase II: $d_\mu < 6 \times 10^{-23}\ e \cdot cm$ ~2030s
- Optimisation of experimental design undertaken progressively
  - Simulation studies
  - Detector prototypes
- Test beam(s) each year to demonstrate feasibility of necessary technical finesses

Phase-I Commissioning



Growing Collaboration!

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国家自然科学基金委员会 National Natural Science Foundation of China

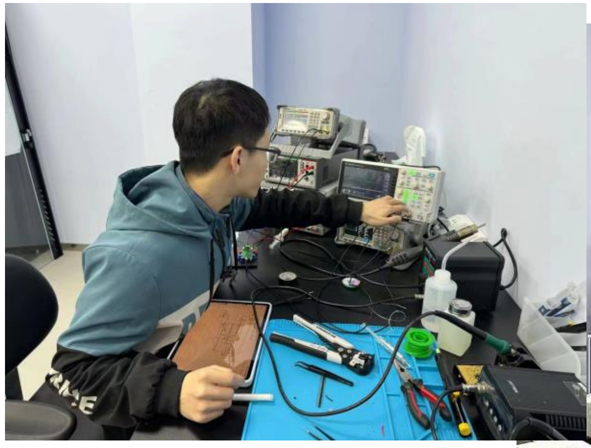
@ TDLI

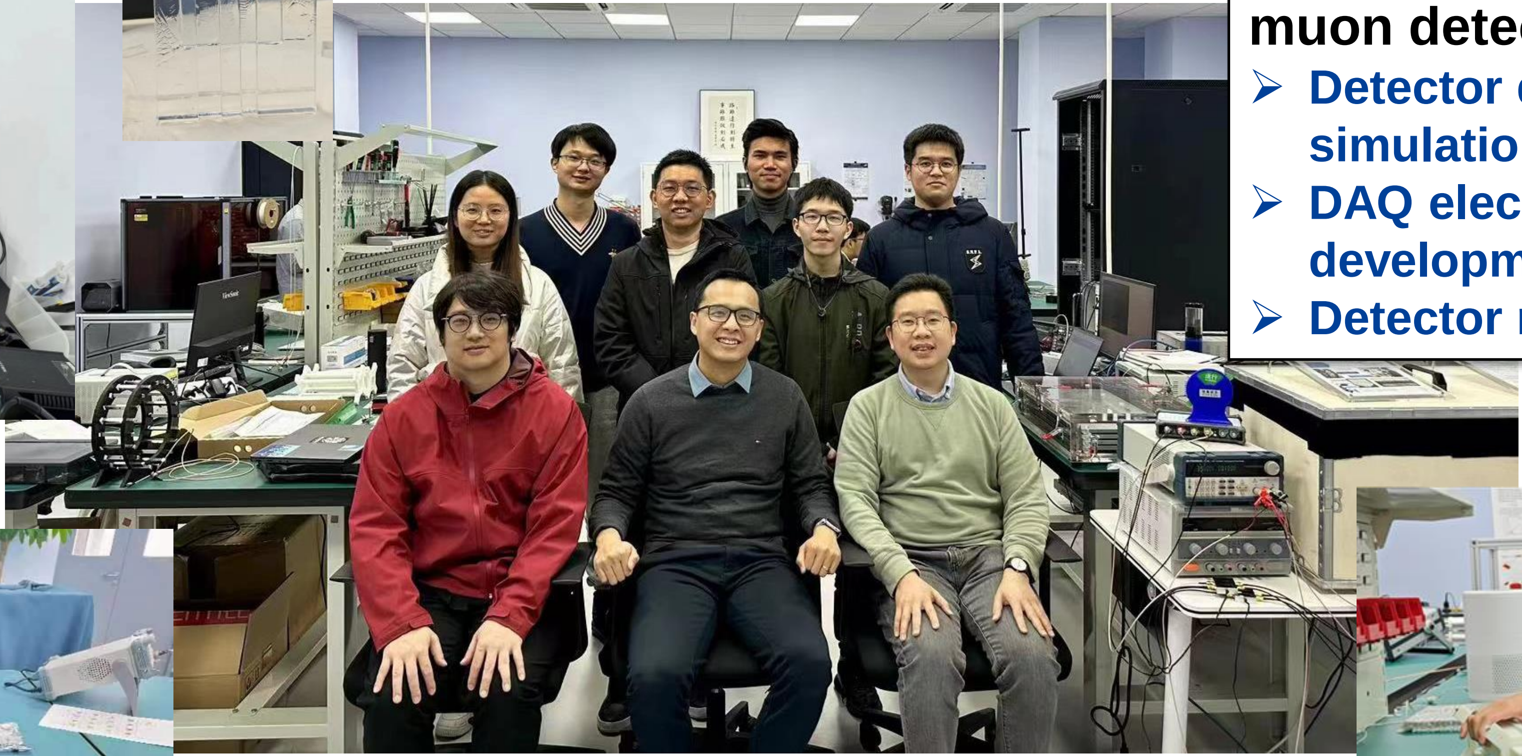
Entrance detector toy mock-up

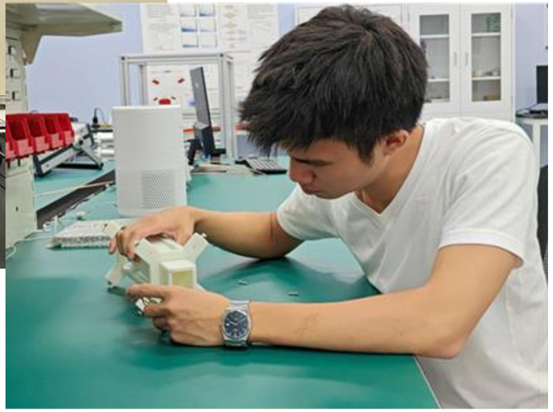
Entrance detector test bench

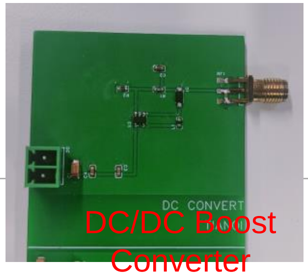
TDLI Muon Group contributes primarily in muon detection

- Detector design with simulation
- DAQ electronics developments
- Detector response tests









DC/DC Boost Converter

Pre-amplifier

Discriminator
< 3 ns delay

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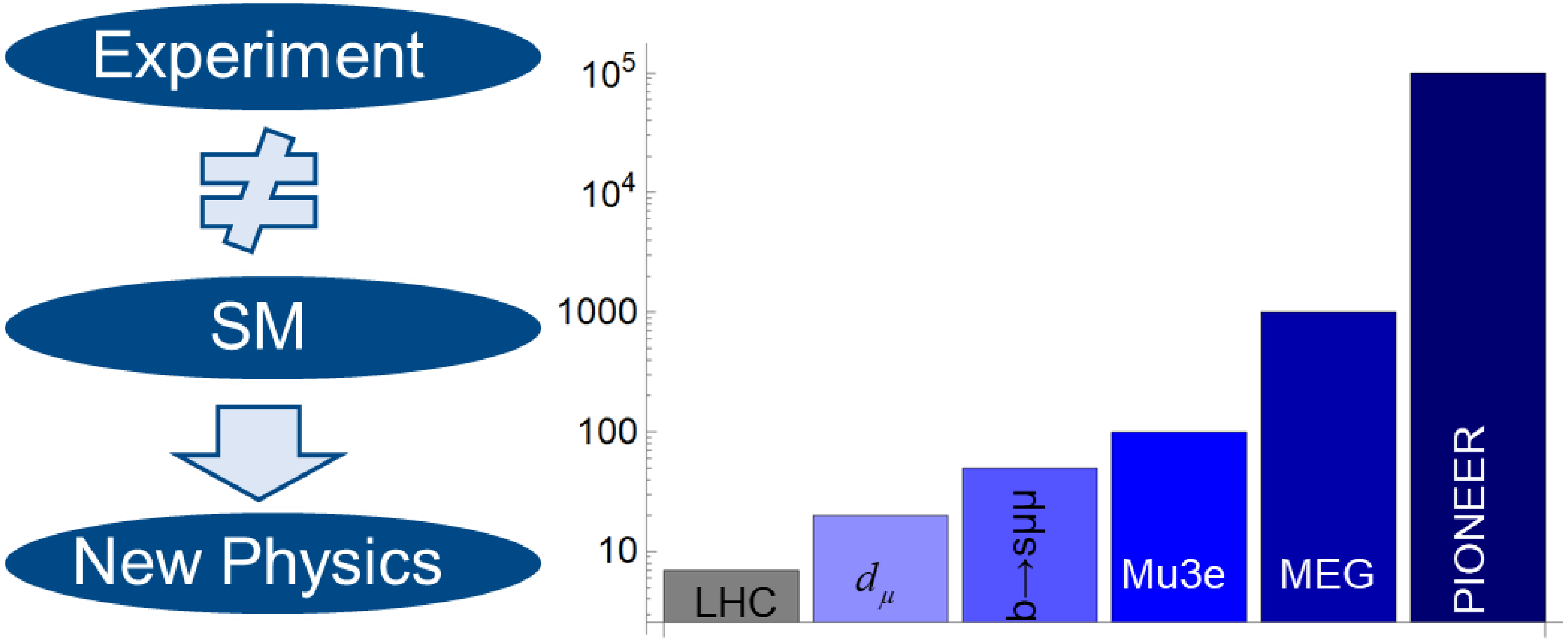
New physics search with Flavours

- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavors



Flavor observables are sensitive to higher energy scales than collider searches

Courtesy Andreas Crivellin

Dipole interactions in EFT: portals to NP

g-2 @ FNAL

ANOMALOUS MAGNETIC MOMENT

$$a_{\ell_i} = -\frac{4m_{\ell_i}}{e}\,\mathrm{Re}\,c_R^{\ell_i\ell_i}$$

Processes intrinsically connected

NP explanation for g-2 is likely to imply large LFV and muon EDM

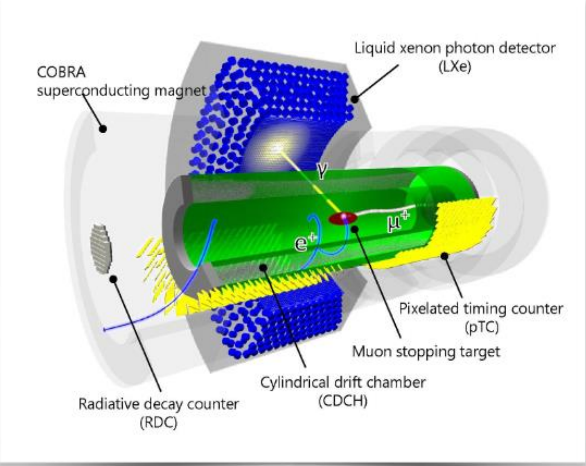
A. Crivellin and M. Hoferichter, arXiv:1905.03789
K. S. Babu, B. Dutta and R. N. Mohapatra, Phys. Rev. Lett. 85 (2000) 5064
E. O. Iltan, Eur. Phys. J. C 54 (2008) 583

$$\mathcal{H}_{\rm eff} = c_R^{\ell_f\ell_i}\,\bar{\ell}_f\sigma_{\mu\nu}P_R\ell_i F^{\mu\nu}$$

This talk

$$d_{\ell_i} = -2\,\mathrm{Im}\,c_R^{\ell_i\ell_i}$$

ELECTRIC DIPOLE MOMENT (EDM)



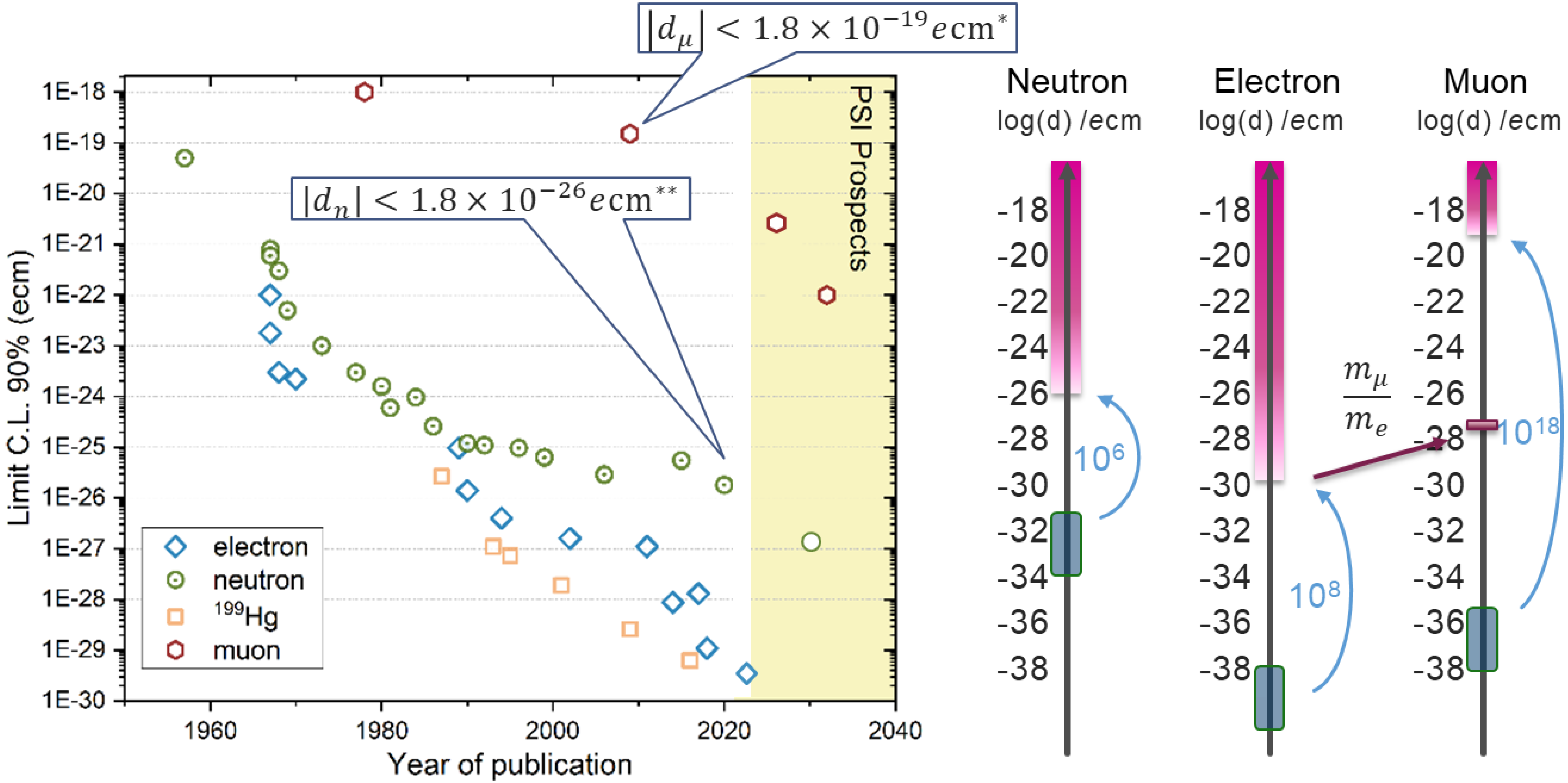
MEG II @ PSI

$$\mathrm{Br}[\mu\to e\gamma] = \frac{m_\mu^3}{4\pi\Gamma_\mu}\left(|c_R^{e\mu}|^2 + |c_R^{\mu e}|^2\right)$$

LEPTON FLAVOUR VIOLATION (LFV)

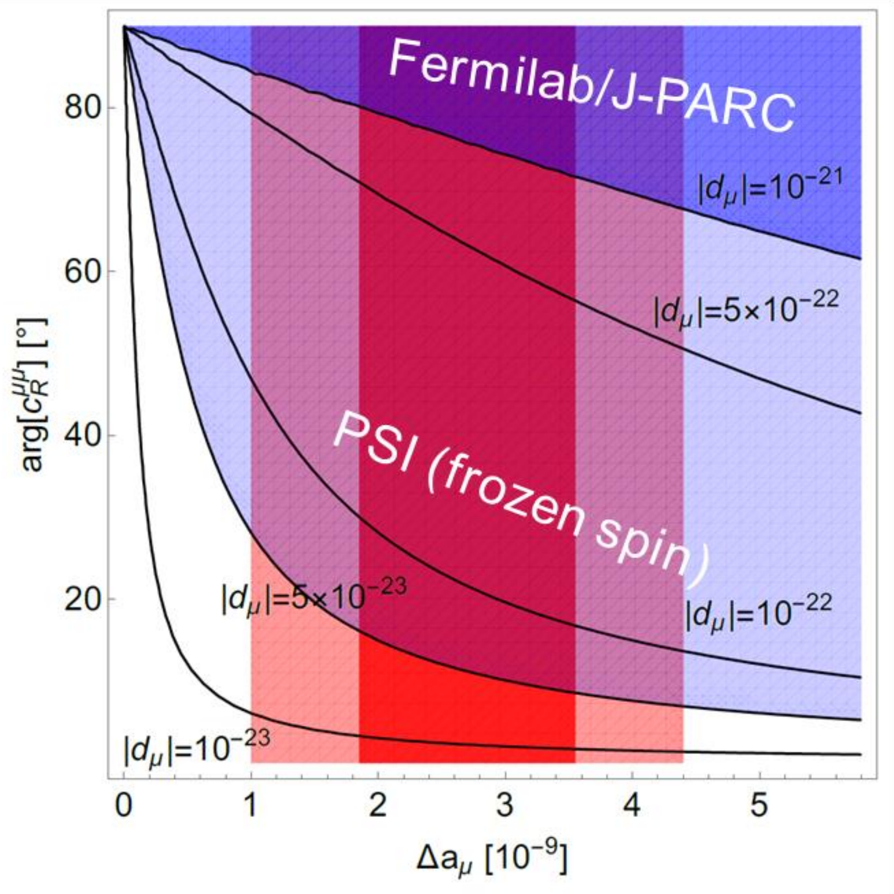
F. Renga @ LNF 2021

A not so brief history on EDM searches



C.f. P-S. Wellenburg

General limits



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

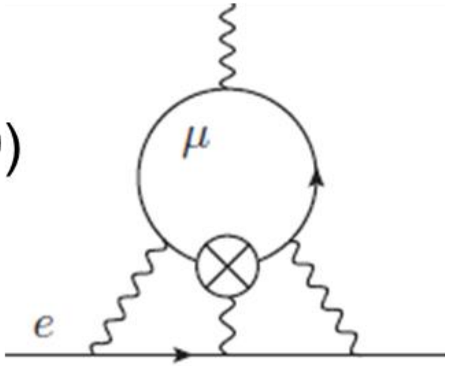
- MFV: $|d^{\mathrm{MFV}}_{\mu\leftarrow e}| < 8.5\times10^{-28}\,e\mathrm{cm}$
- Contribution only starts at the 3-loop level* $|d_{\mu\leftarrow e}| < 4\times10^{-20}\ e\mathrm{cm}$
- Y. Ema et al., PRL**128**, 131801 (2022)

  $|d_\mu(^{199}\mathrm{Hg})| < 6\times10^{-20}\ e\mathrm{cm}$

  $|d_\mu(\mathrm{ThO})| < 2\times10^{-20}\ e\mathrm{cm}$

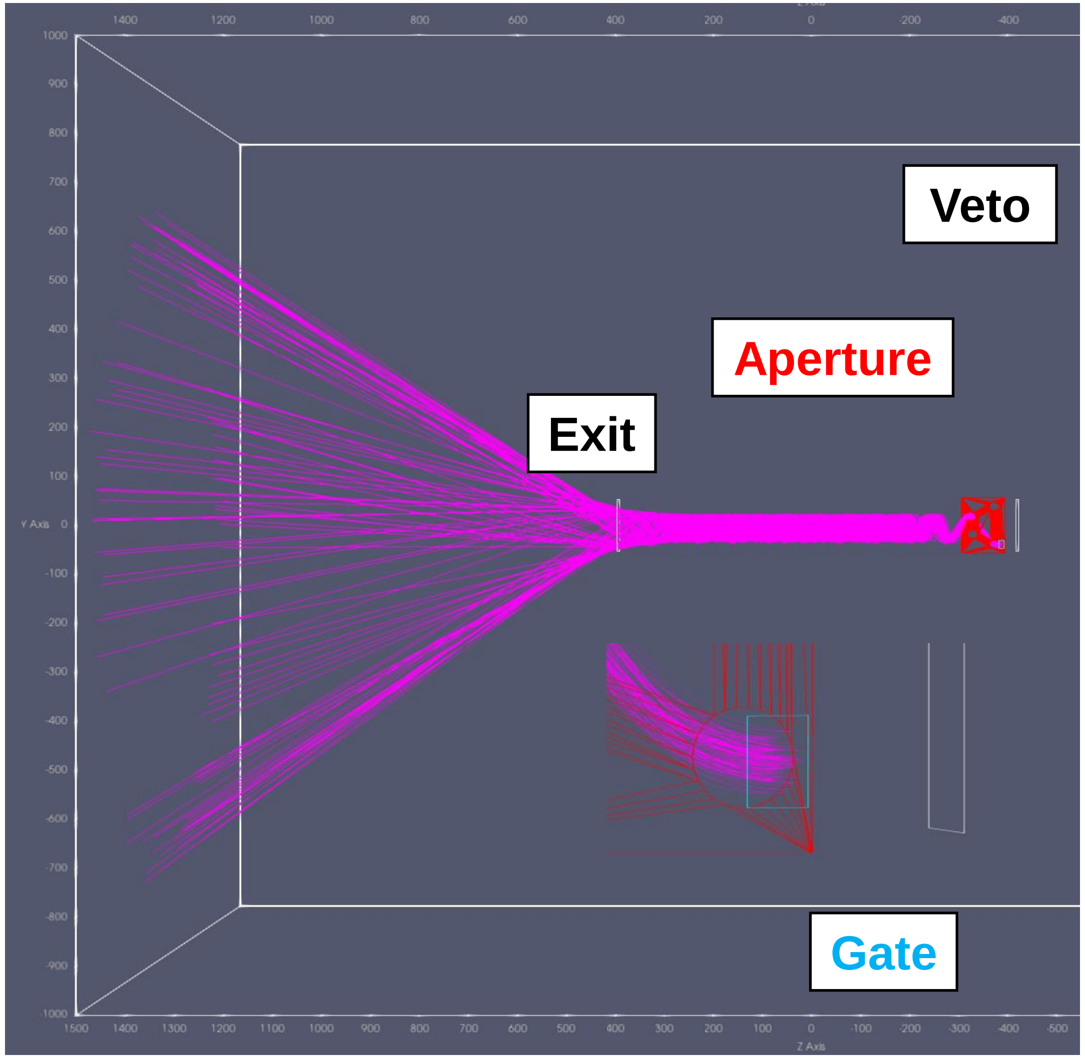
- Bennett et al., PRD80, 052008 (2009)

  $|d_\mu| < 1.5\times10^{-19}\ e\mathrm{cm}$

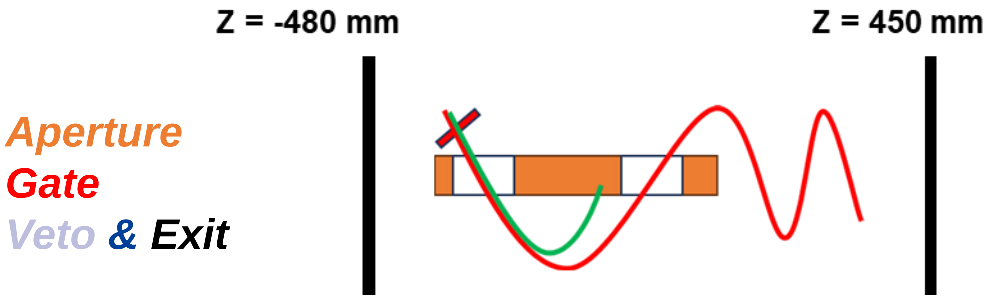


Muon Entrance Detector

Set-up in simulation



Triggers on entrance detector



	Injection, %	Storage, %	Out-of-acceptance, %
Accepted	0.3	100	0
Rejected	99.7	0	100

Detector requirements:

Storable muons Non-storable muons

- Maximising *acceptance rate* and *rejection rate*
- Achieve design that maximises one while minimally compromising the other

Muonphilic Dark Matter

PHYSICAL REVIEW D **102,** 115018 (2020)

Muon g-2 and EDM experiments as muonic dark matter detectors

Ryan Janish[1,2] and Harikrishnan Ramani[1,3,4]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[3]*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*

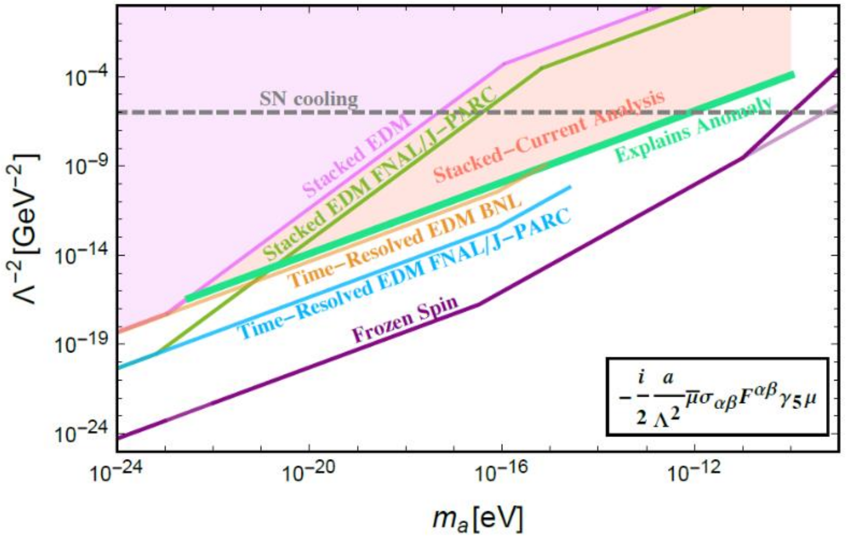
PHYSICAL REVIEW D **103,** 055010 (2021)

Storage ring probes of dark matter and dark energy

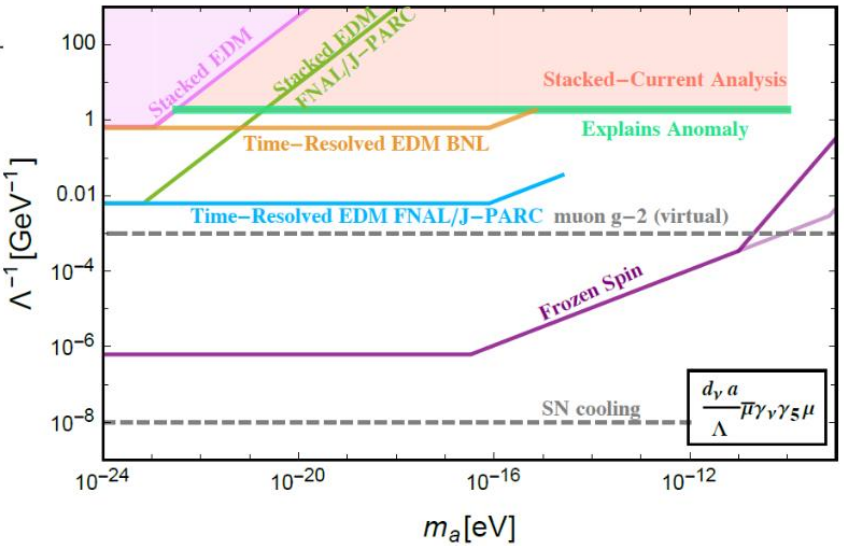
Peter W. Graham,[1] Selcuk Hacıömeroğlu,[2] David E. Kaplan,[3] Zhanibek Omarov,[4,2] Surjeet Rajendran,[3] and Yannis K. Semertzidis[2,4]

[1]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[3]*Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA*
[4]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea*

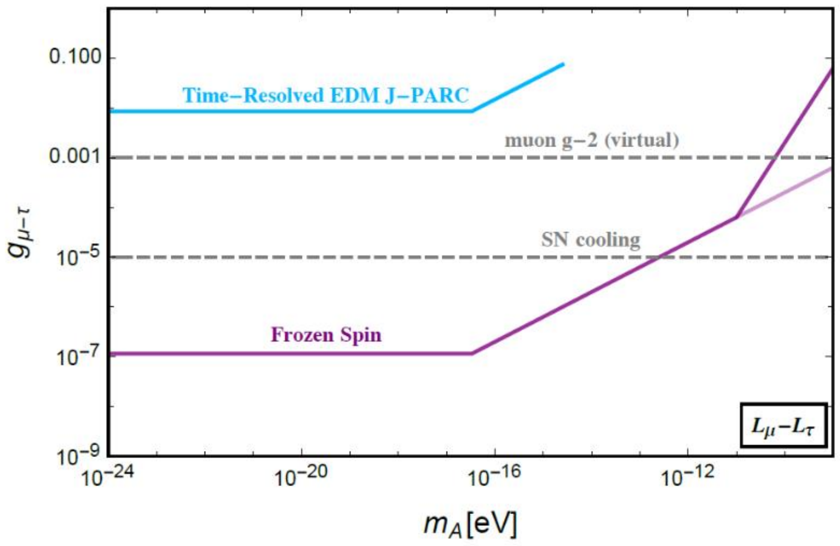
Detection Reach for Muon EDM Coupling



Detection Reach for ALP-Muon Wind

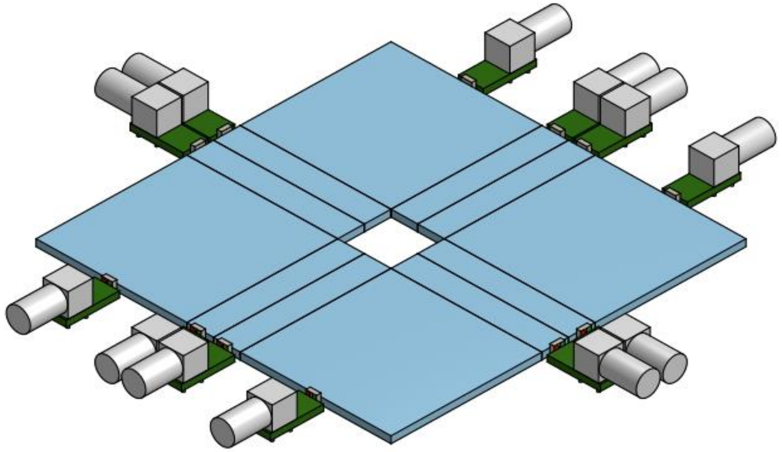


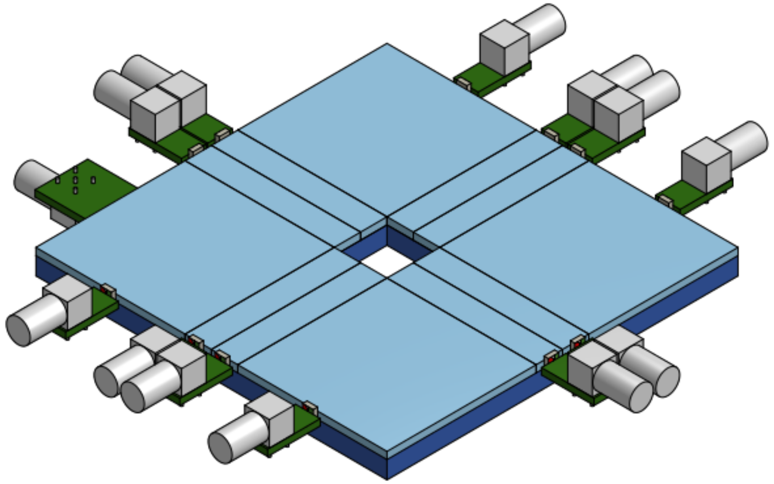
Muonic Vector DM



Muon Entrance Monitor

- **Focus muon beam onto opening of injection channel**
- **Scintillator tiles coupled to SiPMs**
- **Hole in center to let muon beam pass**
- **Front tile thickness 1-2 mm to stop surface muons**
- **A thicker (up to ~5 mm) scintillator layer could be added to better discriminate muons and positrons**
- **Centering procedure optimized in simulation**
- **Next step, prototype building**

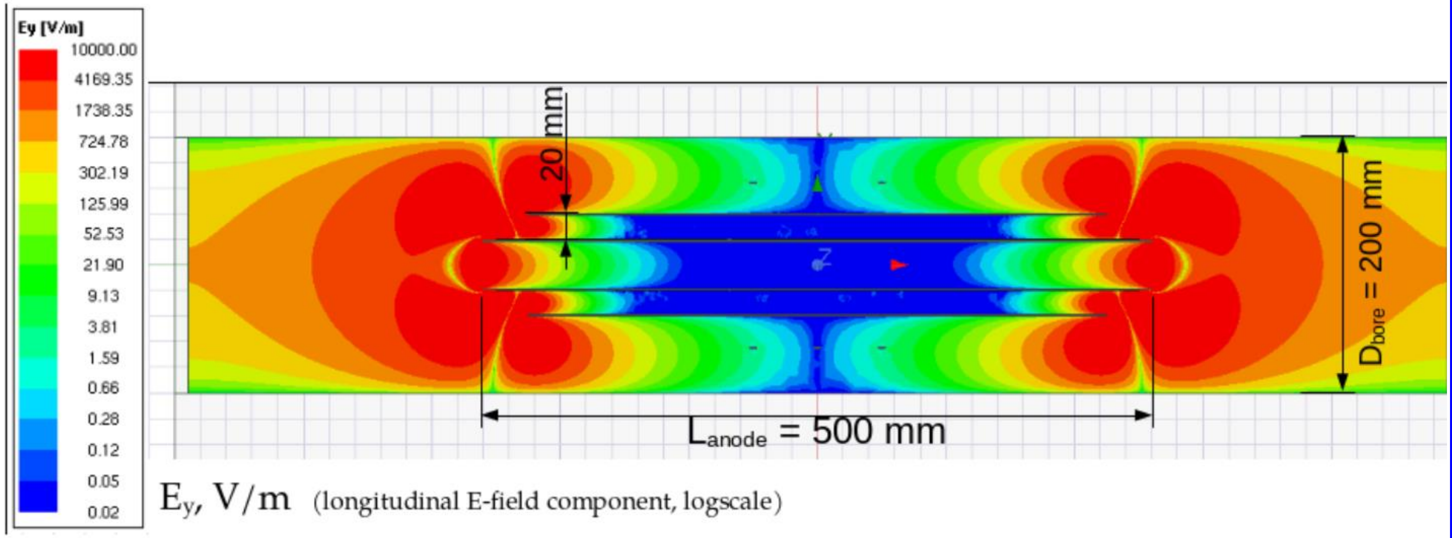


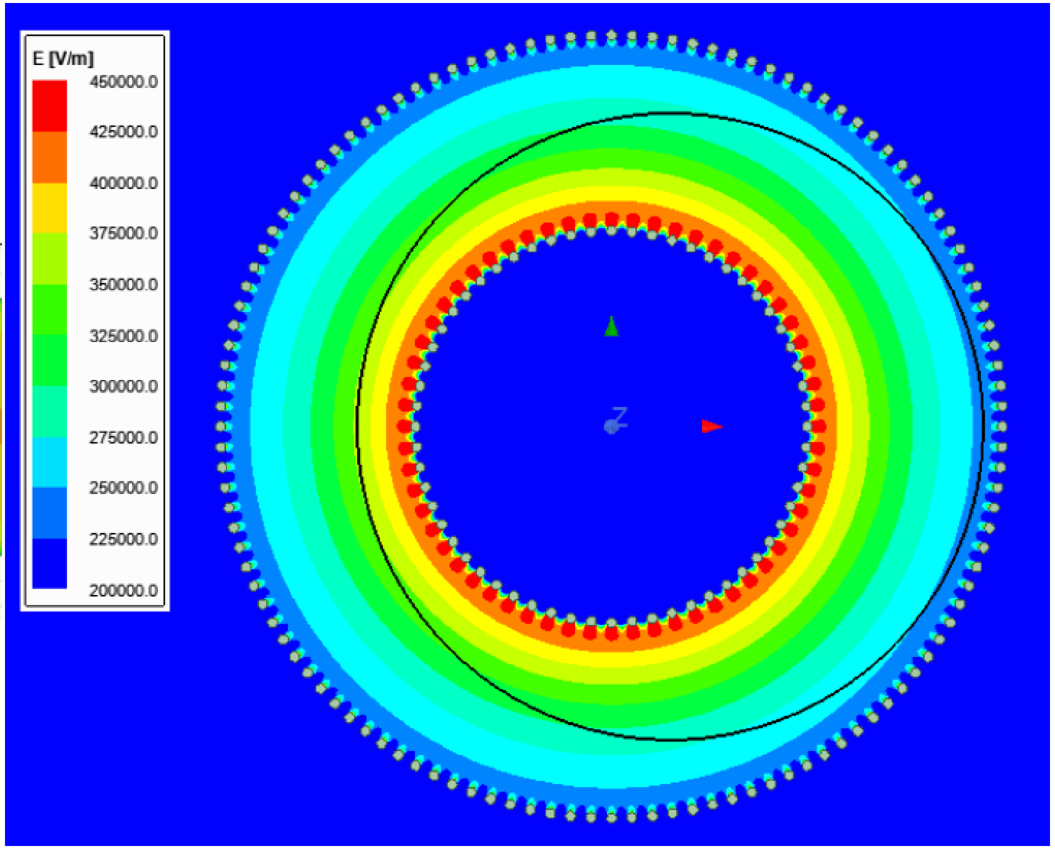


(courtesy L. Morvaj)

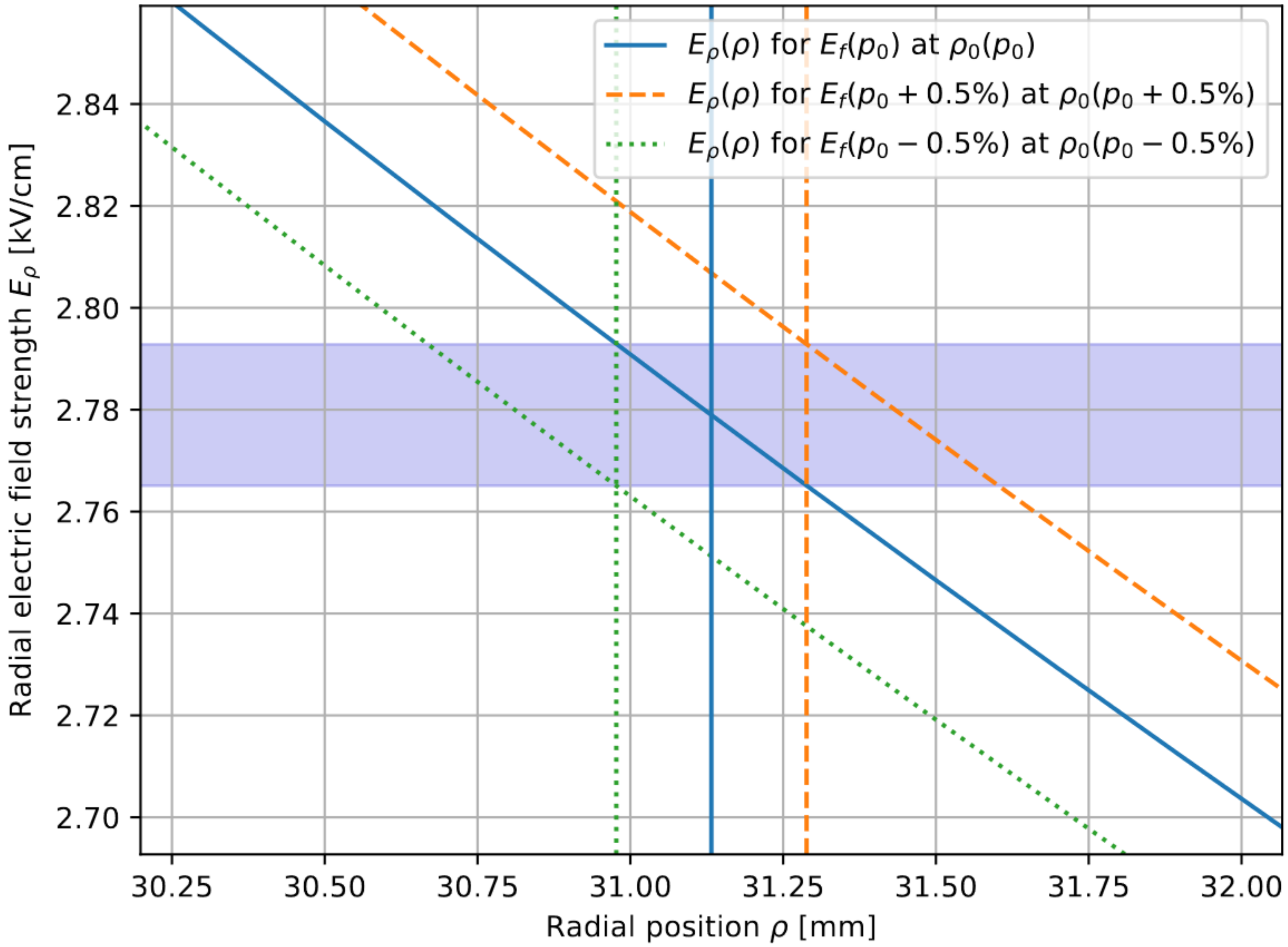
Frozen-spin electrode

Wire electrode simulation



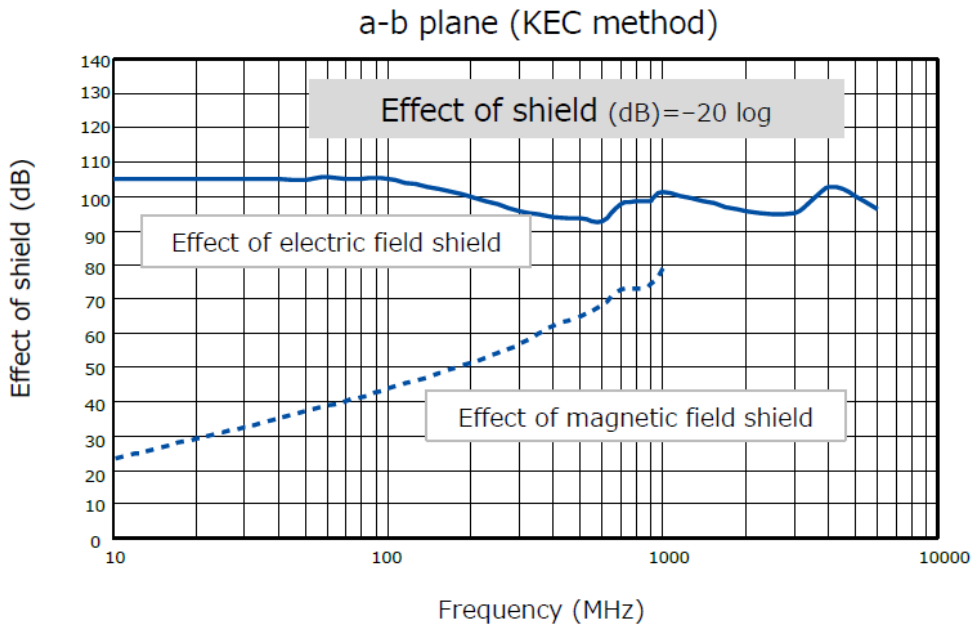


Frozen-spin electrode



Resultant discrepancy of E_f ~1% for momentum bite of 0.5%

Eddy current damping of magnetic pulse



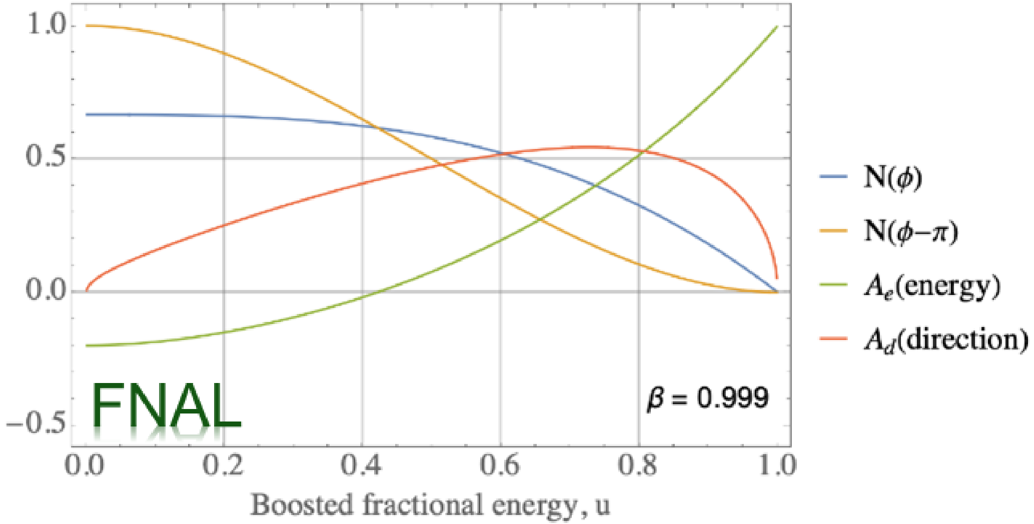
- **Exist off the shelf without substrate down to $17\mu m$**
- **Still considerable damping of magnetic pulse possible**
- **Tests requires**
- **Alternative one dimensional wires (carbon fibers / tungsten)**

Positron detection – figure of merit

Detection of g-2 precession ω_a

- Measurement of mean magnetic field $\langle B \rangle$
- Measure $\omega_a(E)$ to tune electric field to frozen-spin condition

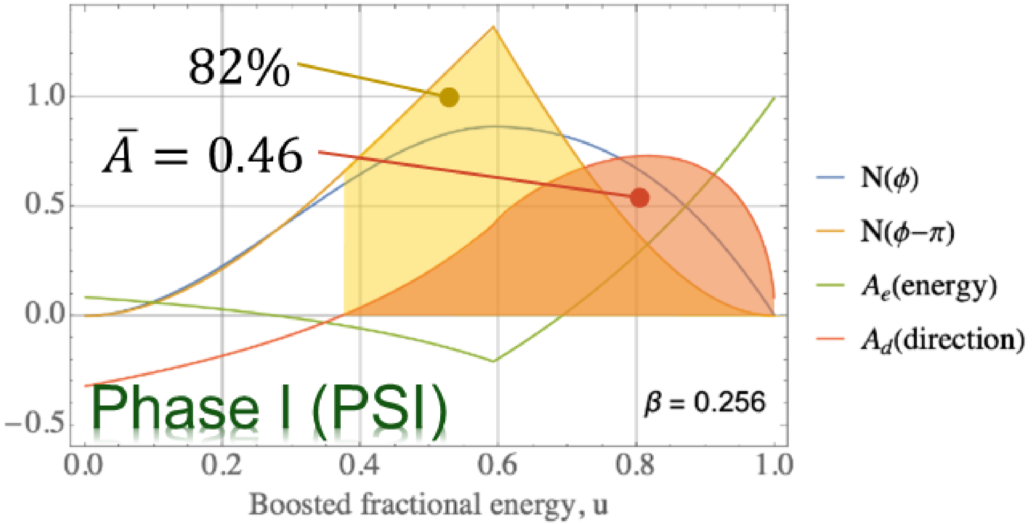
Requires momentum resolution



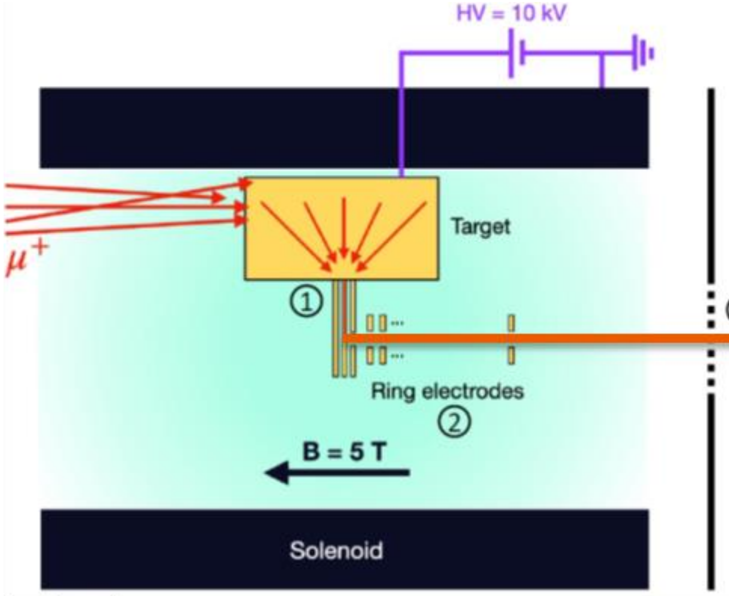
Detection of EDM polarization

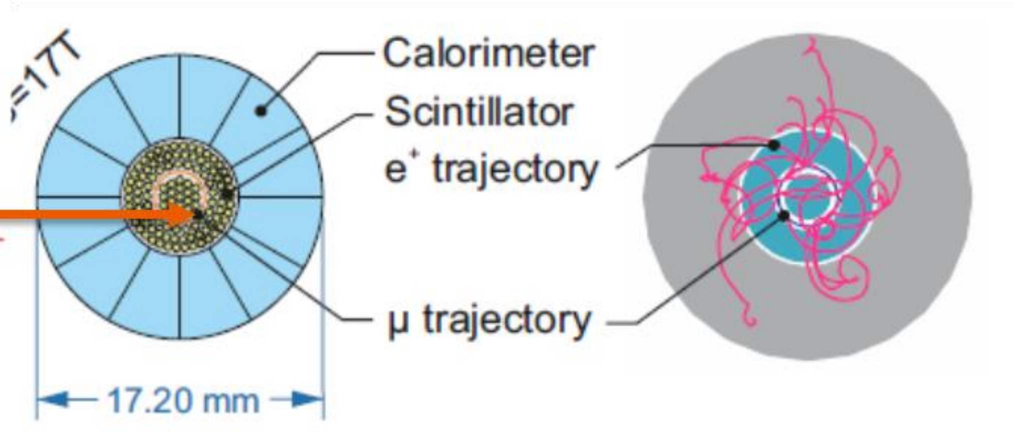
- Measurement of Asymmetry as function of time $A(t)$

Requires spatial resolution along cylinder

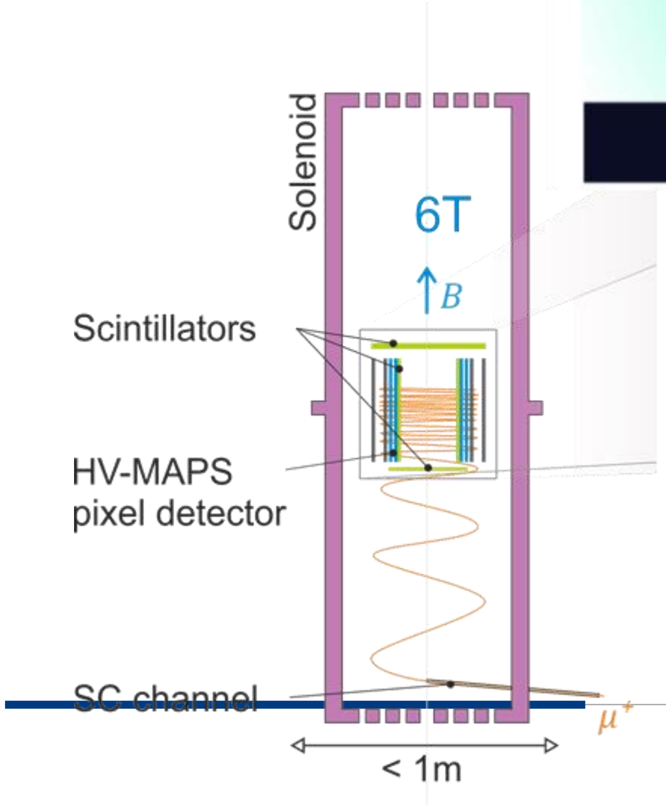


Muon g-2 @ PSI?





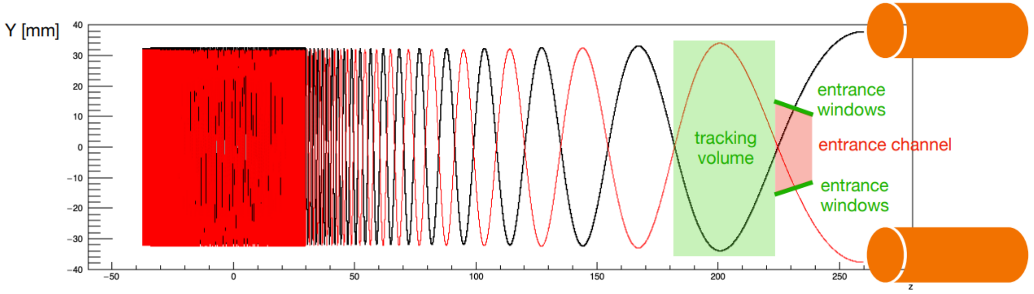
c.f. D. Taqqu

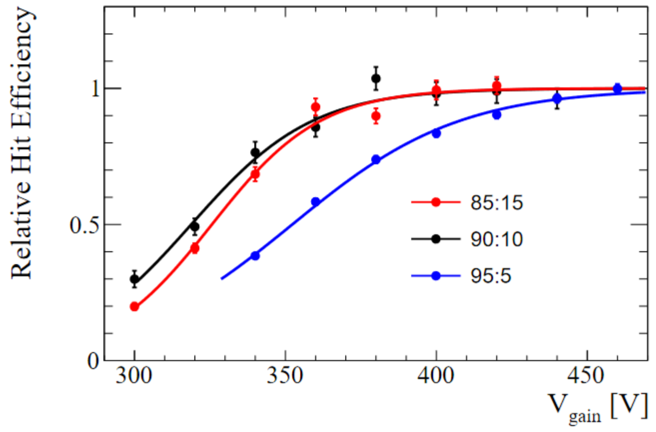


	Fermilab E989	J-PARC	AMMiED	TiAMMo
Muon momentum	30.9 GeV/c	300 MeV/c	125 MeV/c	14.6 MeV/c
Lorentz γ	29.3	3	1.56	1
Polarization	100%	50%	95%	95%
Magnetic field B	1.45 T	3 T	6 T	17 T
Focusing field	E-quadrupoles	weakly focusing (wf)	wf	wf
Cyclotron period	149 ns	7.4 ns	3.8 ns	0.4 ns
AMM precession period	4.37 µs	2.11 µs	1.05 µs	0.37 µs
Number of detected e^+	1.6×10^{11}	5.7×10^{11}	7×10^{12}	1.7×10^{12}
AMM precision (stat.)	0.1 ppm	0.45 ppm	0.1 ppm	0.08 ppm
AMM precision (sys.)	0.1 ppm	0.07 ppm	0.07 ppm	0.07 ppm

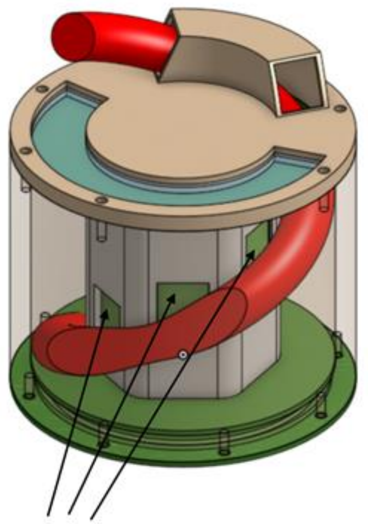
Muon Tracker

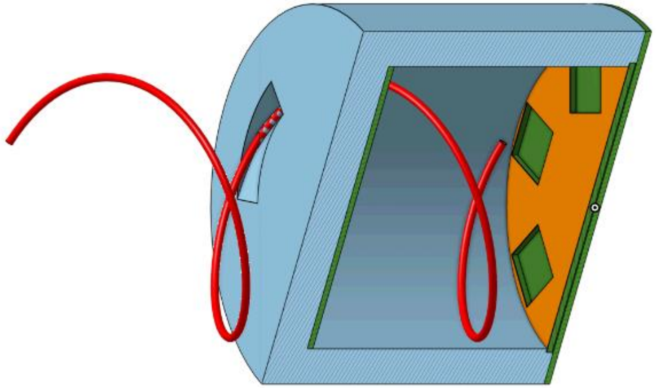
- **Knowledge of muon trajectory is critical for EDM measurement**
  - Ensures nominal muon trajectory for triggering storage pulse kicker
  - Measures injection angle (~ mrad) and muon momentum (~ 0.1%)
  - Systematics cancellation with CW and CCW injection
- **Quasi non-invasive gaseous TPC with high granularity GridPix readout**
  - Light gas mixtures to reduce multiple scattering
  - Prototype tested with single GridPix read out flushed helium-isobutane





Prototype demonstrating GridPix can be used in light mixtures with wide efficiency plateau





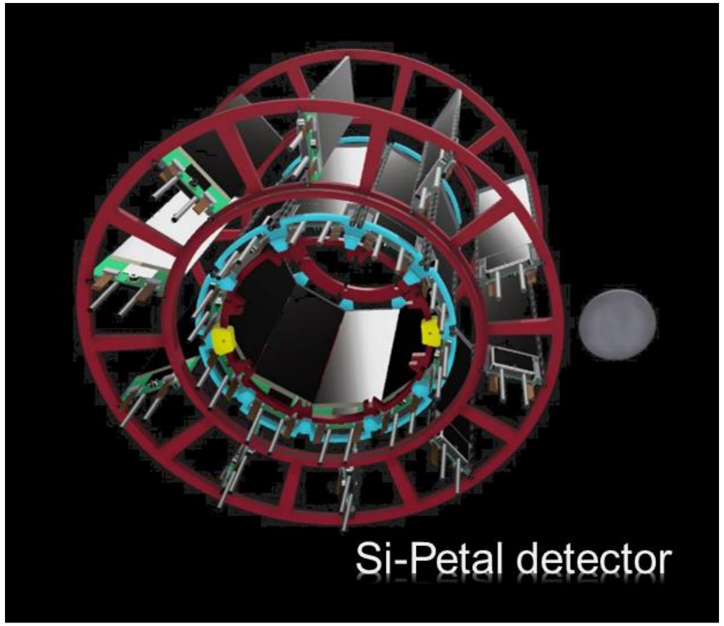
Cross-section view

Courtesy of F. Renga

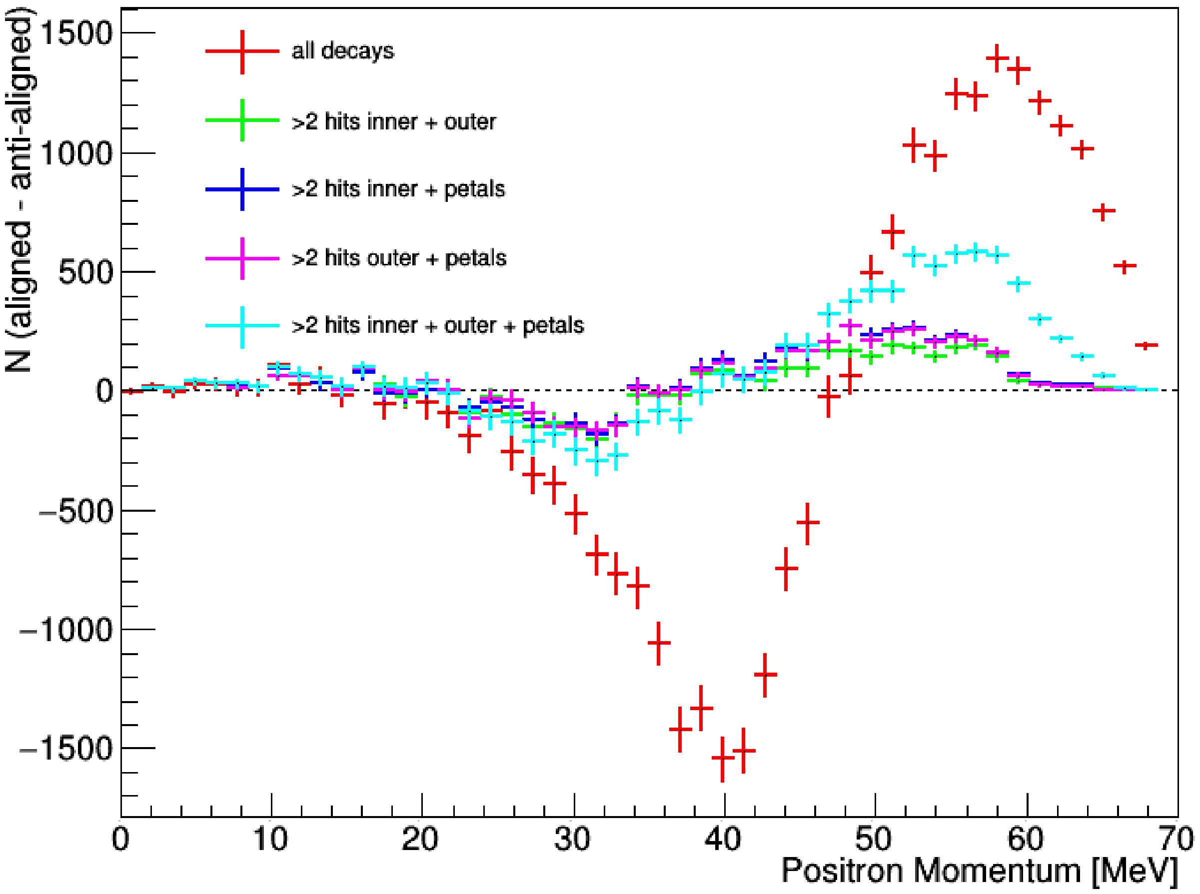
Positron Detection: g-2 Measurement

- **Silicon strip detectors to tune frozen-spin electric field, E_f**
- **Measures forward-backward asymmetry of positrons**
- **Two cylindrical layers + petals**
- $\Delta p \approx 5\mathrm{MeV/c}$; $\Delta t \approx 2\mathrm{ns}$; $\Delta \mathrm{R} \approx 0.1\mathrm{mm}$

Design constrained by momentum acceptance of storage region and solenoid bore



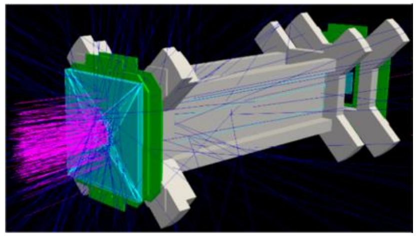
Sensitivity of AMM measurement

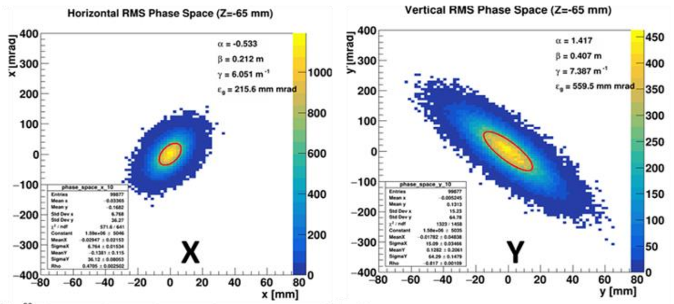


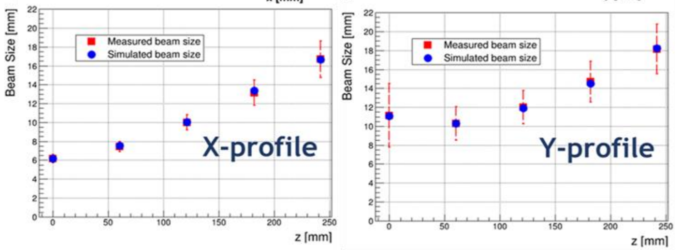
Test Beam 2022 Simulation

Verification of prototype entrance detector response

Test beam model in simulation → Reproduction of optical response → Reproduction of relative event rates

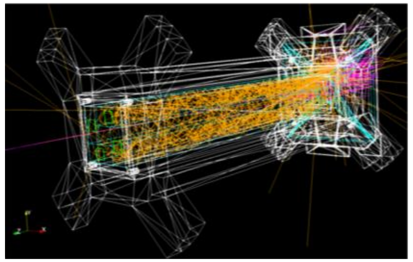




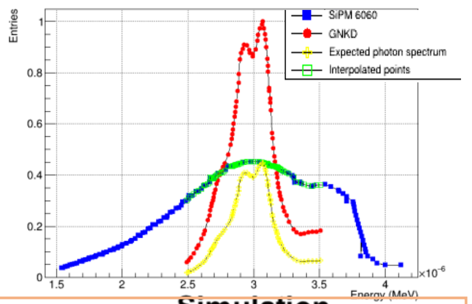


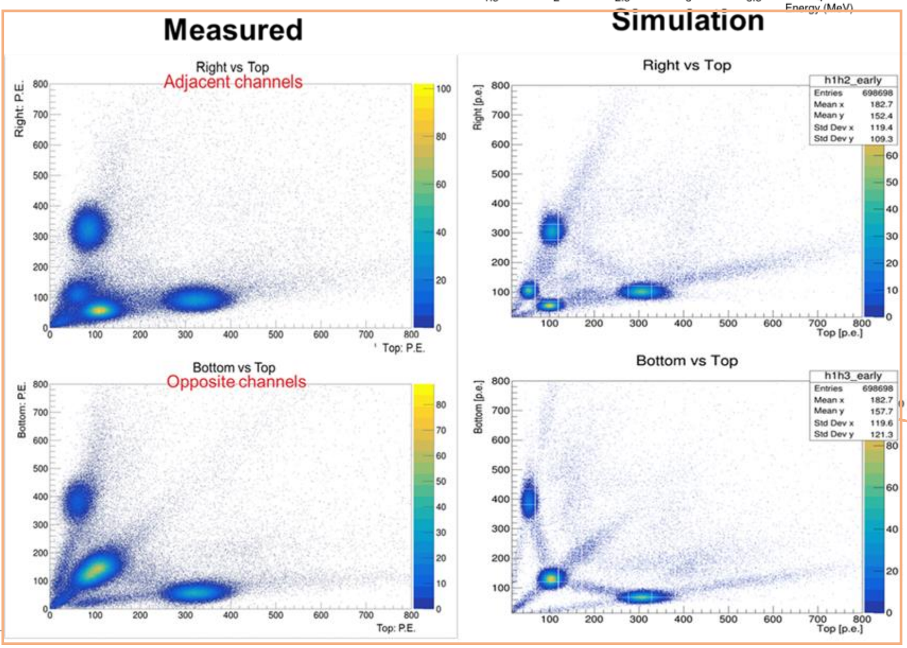
Measured beam profiles reproduced in simulation for input of detector performance studies

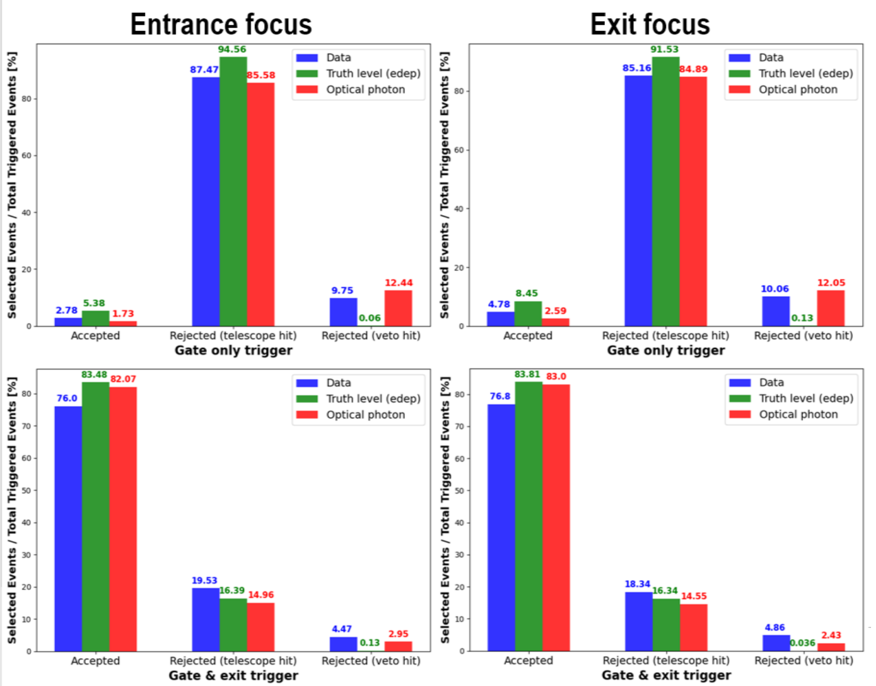
Optical photon propagation in prototype detector



Emission spectrum of SiPM and scintillator





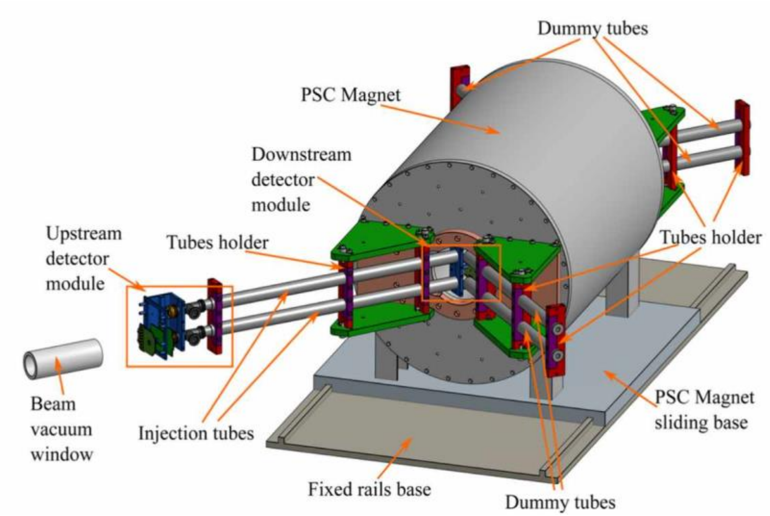


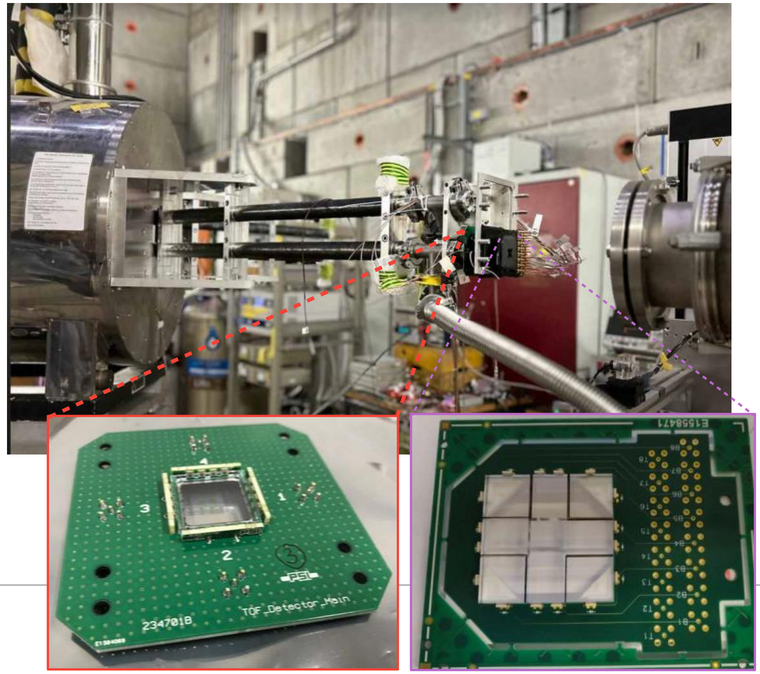
Optical response of detector studied by reproducing measured optical photon distribution

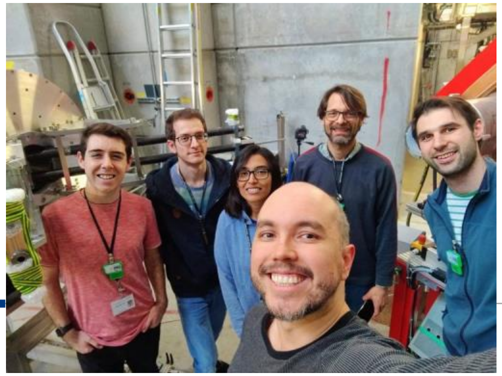
Measured event rates studied at truth level simulation and replicated with optical photon

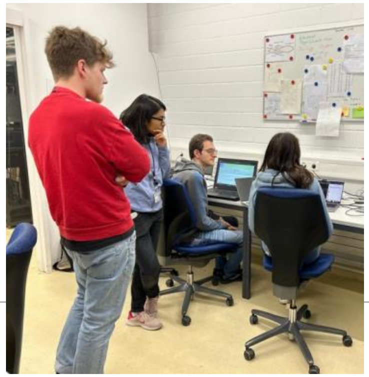
Test beam – December 2023

- **Show control of the momentum of injected muons by measuremens of the ToF through injection tubes.**
- **Reproducibility of muon momentum distribution for positive and negative magnetic field.**
- **Fringe field shielding and hysteresis studies.**
- **Tests of a beam monitor to center the beam on the injection channel.**









Systematics cancellation

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1. $B_r \neq 0$
2. Misalignment of B and E planes
3. Electric field not on a plane —> magnetic precession in the rest frame —> vertical precession in the lab frame
4. Residual (g-2) precession + locally non-horizontal orbit = vertical precession
5. $B_\theta \neq 0$
6. Early-to-late detector effects

Vertical orbit oscillations!
Average to 0, but can deteriorate the quality of the asymmetry fit

Can be canceled by comparing ***clockwise (CW)*** *and* ***counter-clockwise (CCW)*** *injection*

CW vs. CCW

\+

Single muon storage avoids high detector rates changing with time

\+

injection effects measured without muons

F. Renga @ LNF 2021