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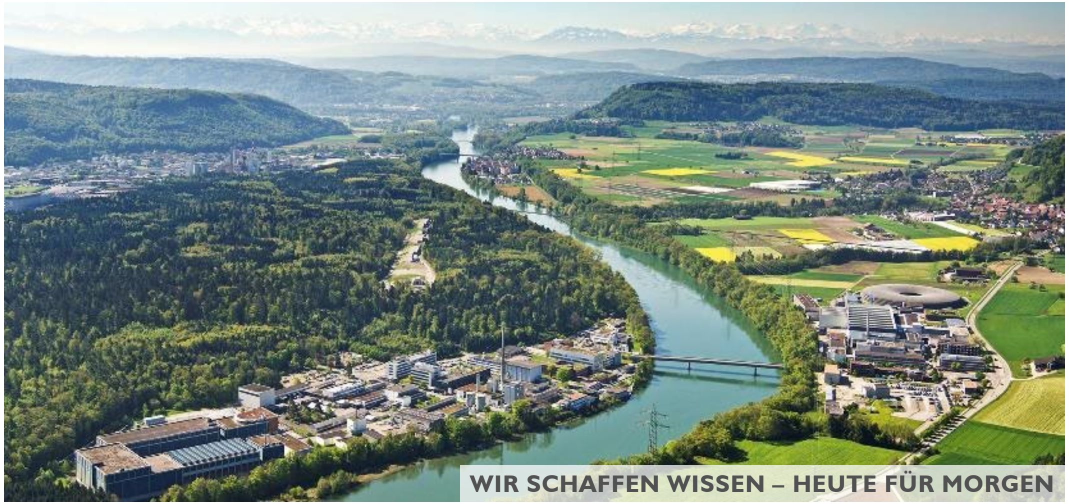
PSI



Philipp Schmidt-Wellenburg :: Scientist :: Paul Scherrer Institute

Search for a muon EDM

New physics searches at the precision frontier, Seattle, 05/10/23

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
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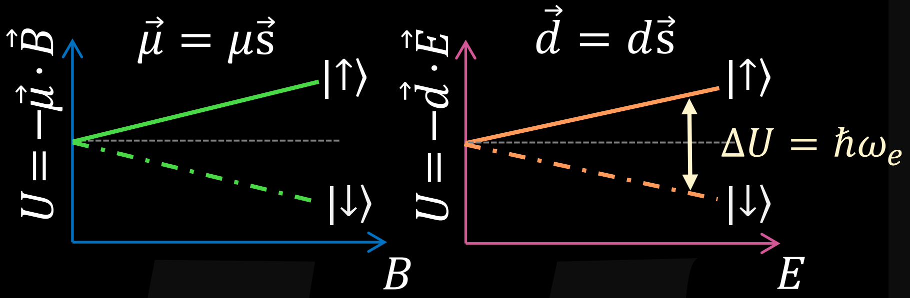
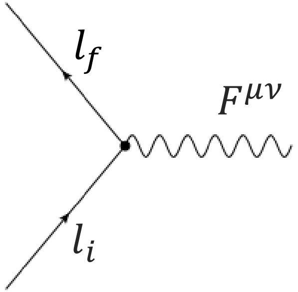
CP violation & edm



Lepton form factors and dipole moments



Effective Hamiltonian: $$\mathcal{H}_{\text{eff}} = c_R^{l_f l_i} \bar{l}_f \sigma_{\mu\nu} P_R l_i F^{\mu\nu} + \text{h.c.}$$

magnetic-dipole

Anapole - moment

$$\langle p' | J_\mu^{\text{EM}} | p \rangle = \bar{\Psi}(p') \left[F_1 \gamma_\mu + \frac{iF_2}{2M} \sigma_{\mu\nu} q^\nu + \frac{iF_3}{2M} \sigma_{\mu\nu} \gamma_5 q^\nu + \frac{F_4}{M^2} (q^2 \gamma_\mu - \gamma^\mu q_\mu q_\mu) \right] \Psi(p)$$

charge

electric-dipole

$$\delta F_2 = a_{l_i} = -\frac{2m_{l_i}}{e} \left(c_R^{l_i l_i} + c_R^{l_i l_i *} \right) = -\frac{4m_{l_i}}{e} \text{Re}\, c_R^{l_i l_i}$$

$$F_3 = d_{l_i} = i \left(c_R^{l_i l_i} - c_R^{l_i l_i *} \right) = -2\text{Im}\, c_R^{l_i l_i}$$

Lepton dipole moments (non-relativistic)

Non relativistic Hamiltonian: $\mathcal{H} = -\mu\vec{s}\cdot\vec{B} - d\vec{s}\cdot\vec{E}$ $\quad|\vec{s}| = 1$

The magnetic μ and electric d dipole moment of a lepton are defined by

$$\mu = \frac{gq}{2m}\frac{\hbar}{2} \qquad d = \frac{\eta q}{2mc}\frac{\hbar}{2}$$

$$\vec{\omega}_L = \frac{gq}{2m}\vec{B} \qquad \vec{\omega}_E = \frac{\eta q}{2mc}\vec{E}$$

For leptons:

$g = 2 + 2a$

$d = 0 + 10^{-36}ecm$

Lepton spin precession and motion in a B-field

Relativistic lepton spin precession in a perpendicular magnetic field

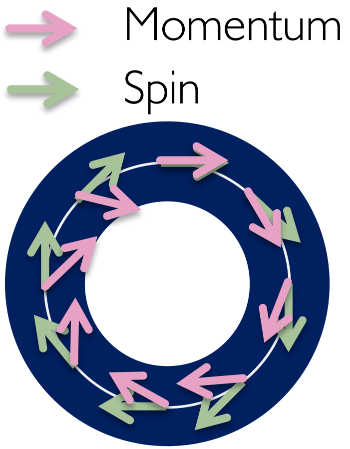
$$\vec{\omega}_L = \frac{gq\vec{B}}{2m} + (1-\gamma)\frac{q\vec{B}}{\gamma m} = \frac{aq\vec{B}}{m} + \frac{q\vec{B}}{\gamma m}$$

Cyclotron frequency of a lepton in a perpendicular magnetic field

$$\vec{\omega}_C = \frac{q\vec{B}}{\gamma m}$$

Measurement of the anomalous magnetic moment by observing relative precession

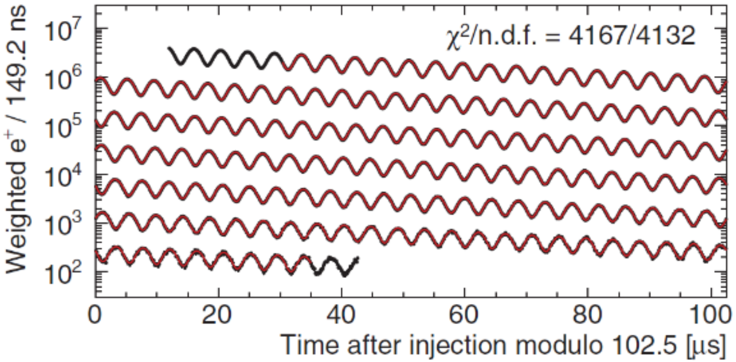
$$\vec{\omega}_a = \vec{\omega}_C - \vec{\omega}_L = -\frac{q}{m}a\vec{B}$$



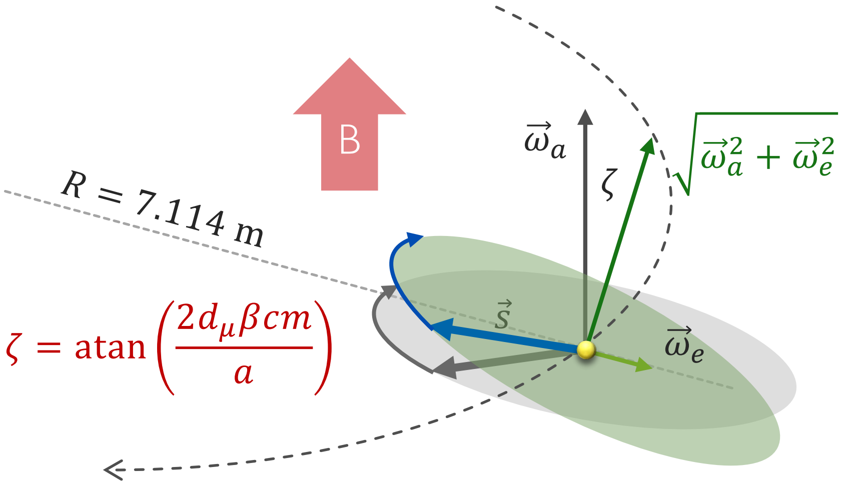
Muon dipole moments and frequencies

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

g-2 term ω_a



FNAL* & JPARC**: $\sigma(d_\mu) \approx 10^{-21} e\text{cm}$



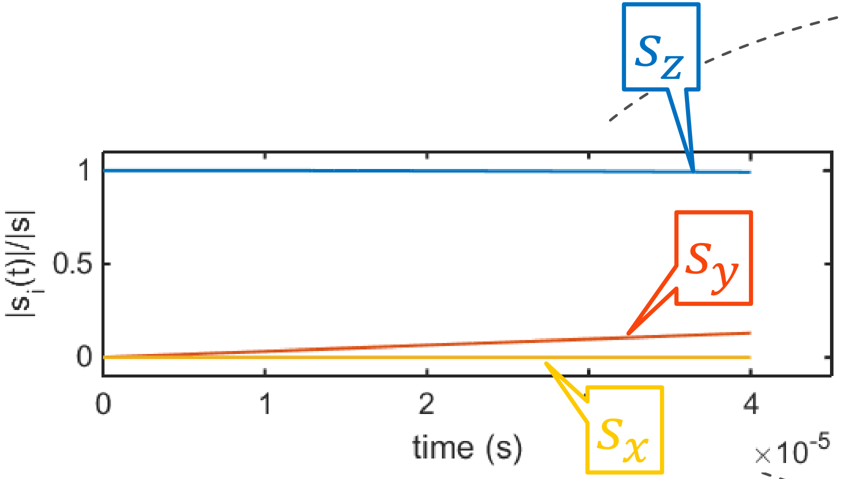
Muon dipole moments –freezing the spin at PSI

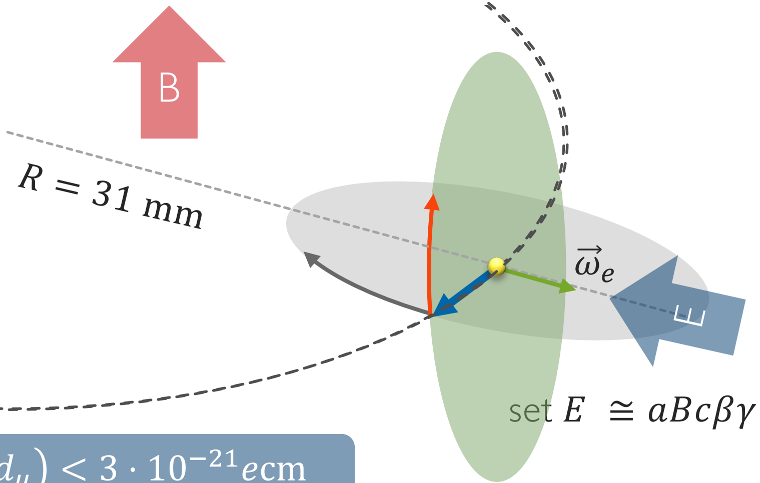
$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\Bigg]$$

g-2 term ω_a

EDM term ω_e

Frozen-spin potential at PSI: $\sigma(d_\mu) < 6 \cdot 10^{-23} ecm$



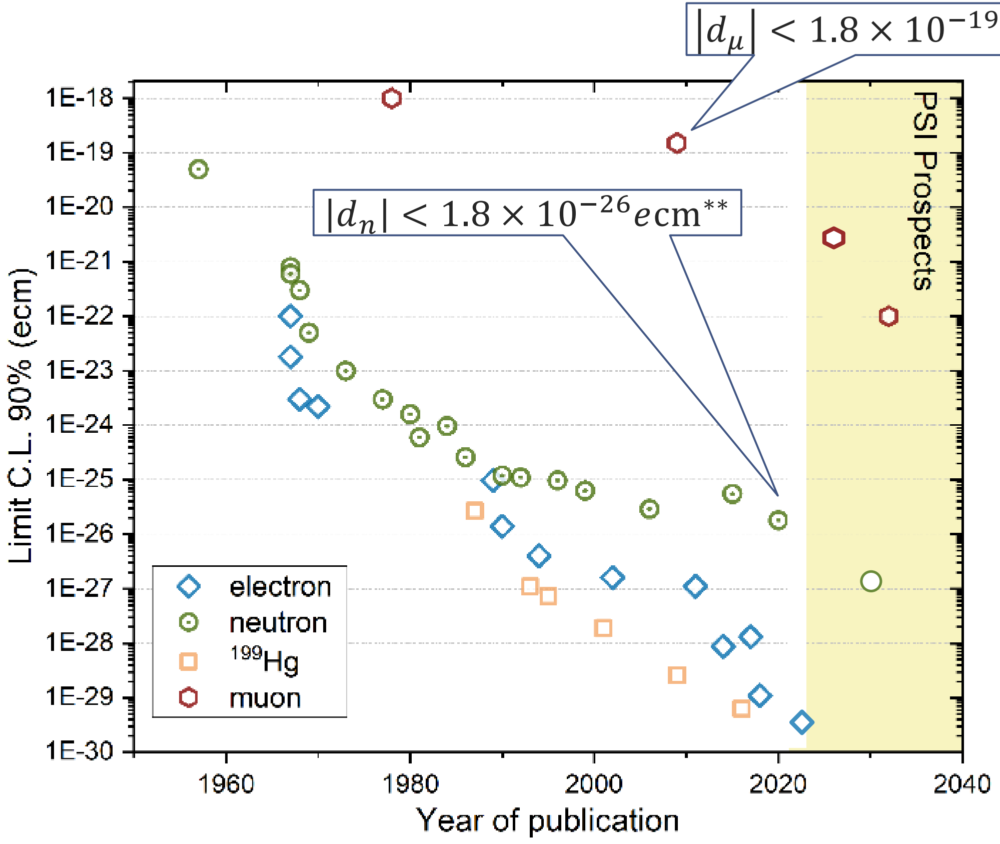


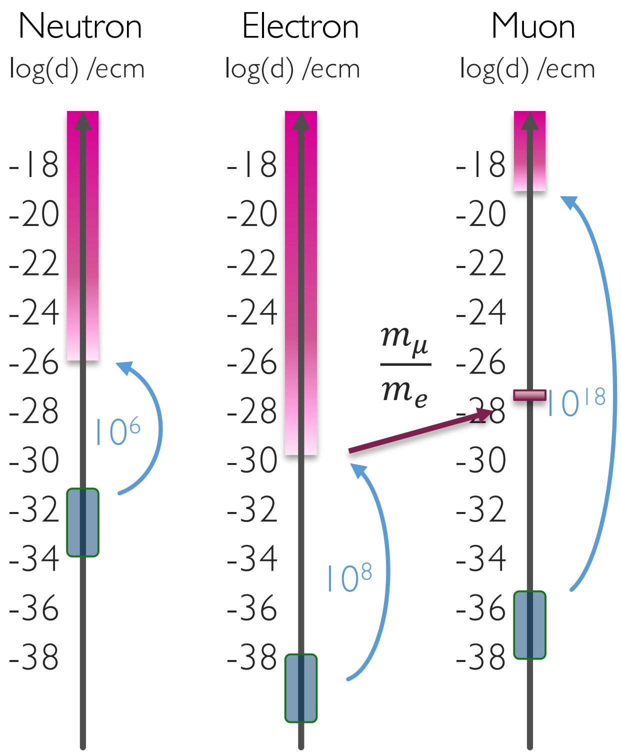
set $E \cong aBc\beta\gamma^2$

Phase I: $\sigma(d_\mu) < 3 \cdot 10^{-21} ecm$

[*Farley et al,, PRL93 042001 (2004)] ,

A not so brief history of EDM searches

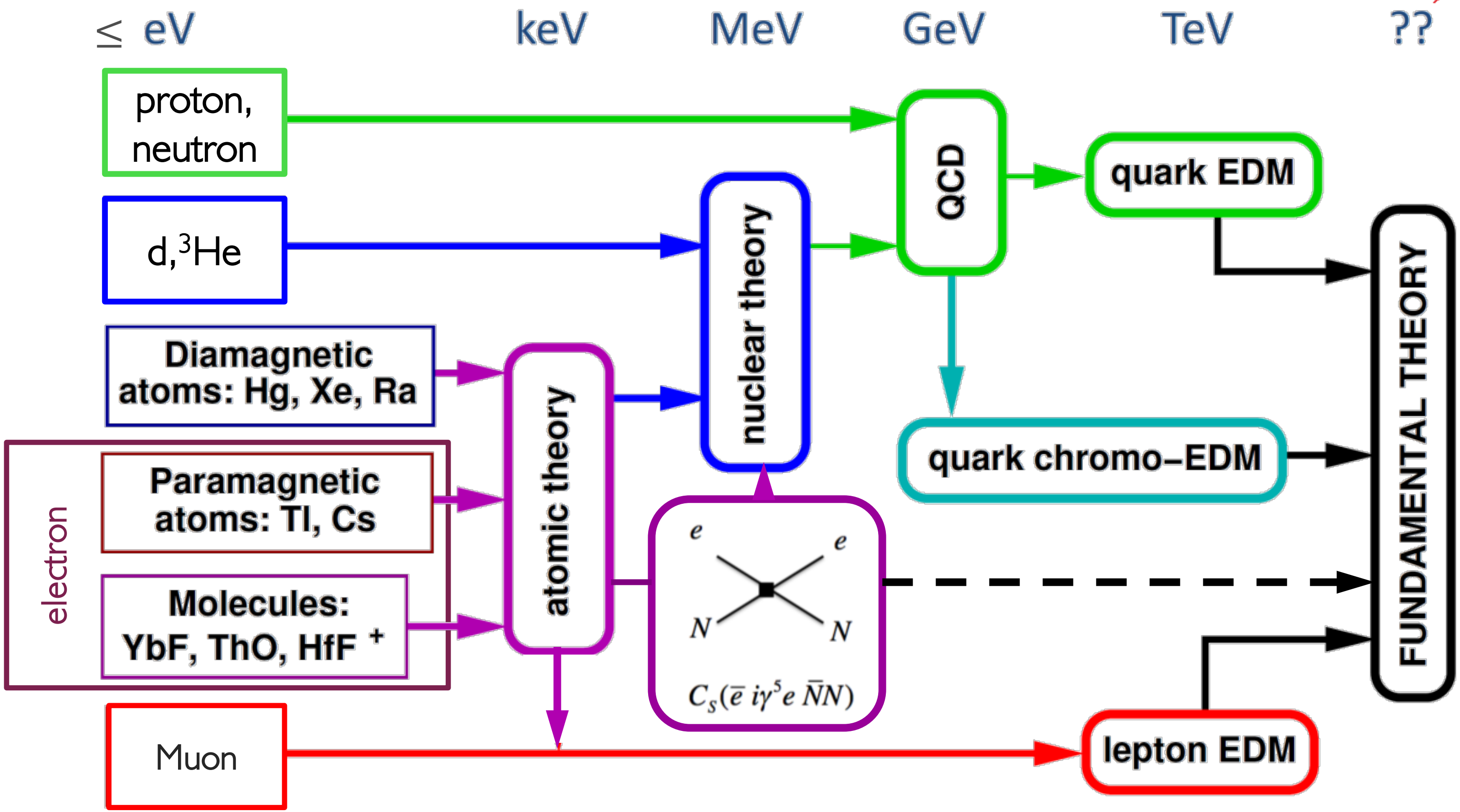




*Bennett et al., PRD80(2009)052008

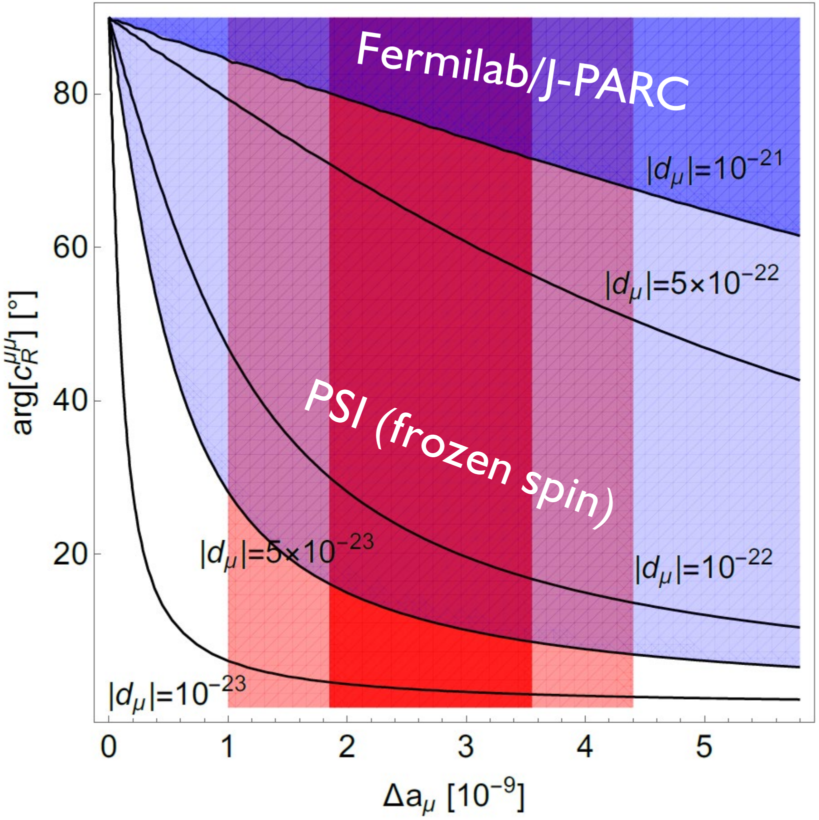
** Abel et al., PRL124(2020)081803

Complementarity of EDM searches



Scheme: adapted from Rob G.E.Timmermans

General limits on μEDM



- MFV: $\left|d_{\mu\leftarrow e}^{\mathrm{MFV}}\right| < 8.5\times10^{-28} e\mathrm{cm}$
- Contribution only starts at the 3-loop level*

$$\left|d_{\mu\leftarrow e}\right| < 4\times10^{-20}\ e\mathrm{cm}$$

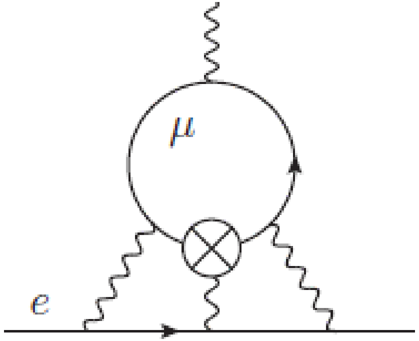
- Y. Ema et al., PRL **128**, 131801 (2022)

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

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

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

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



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

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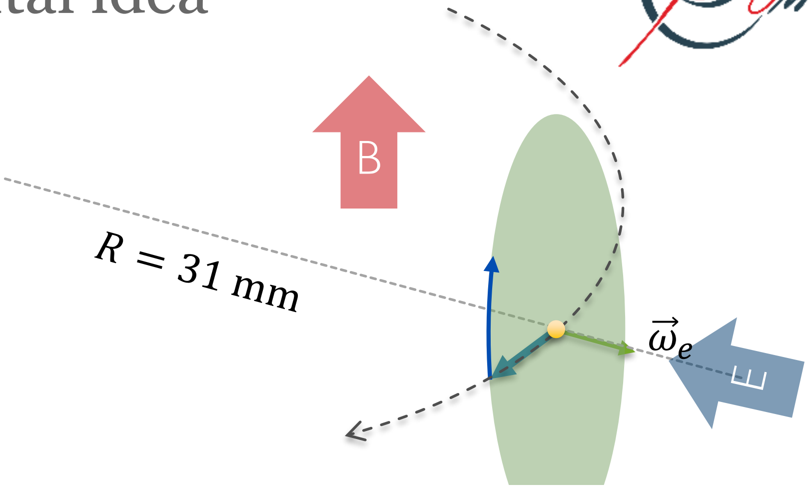
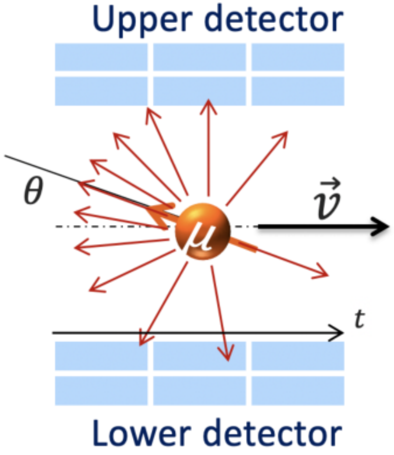
The general experimental idea

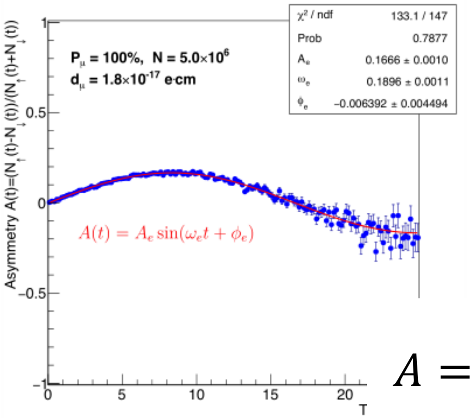
- If the EDM $\neq 0$, then there will be a vertical precession out of the plane of the orbit
  - An asymmetry increasing with time will be observed recording decay positrons



- If the EDM $= 0$, then the spin should always be parallel to the momentum
  asymmetry should be zero

- **Some asymmetry could still be observed due to systematic effects**

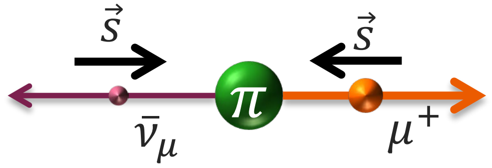




$$A = \frac{N_u - N_d}{N_u + N_d}$$

μ-polarization and analysis

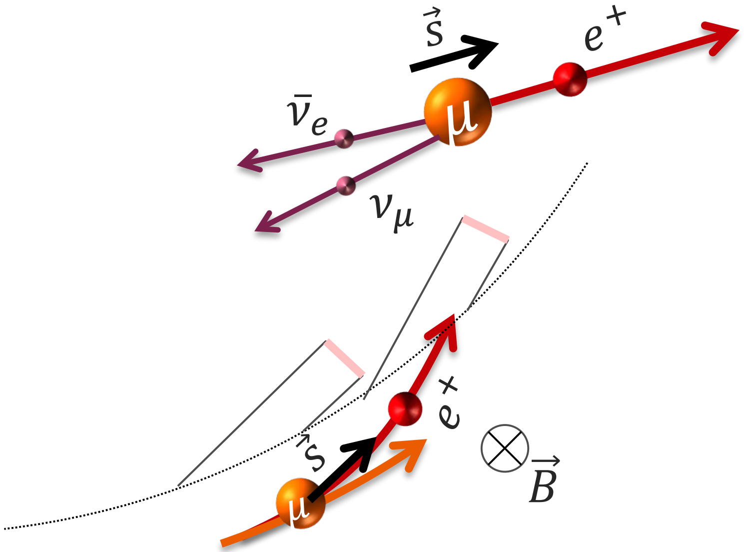
- Weak decay $\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ result in $P_\mu \approx 95\%$ for $p_\pi \sim 220\mathrm{MeV}/c^2$ backward decay in $P_\mu \approx 95\%$



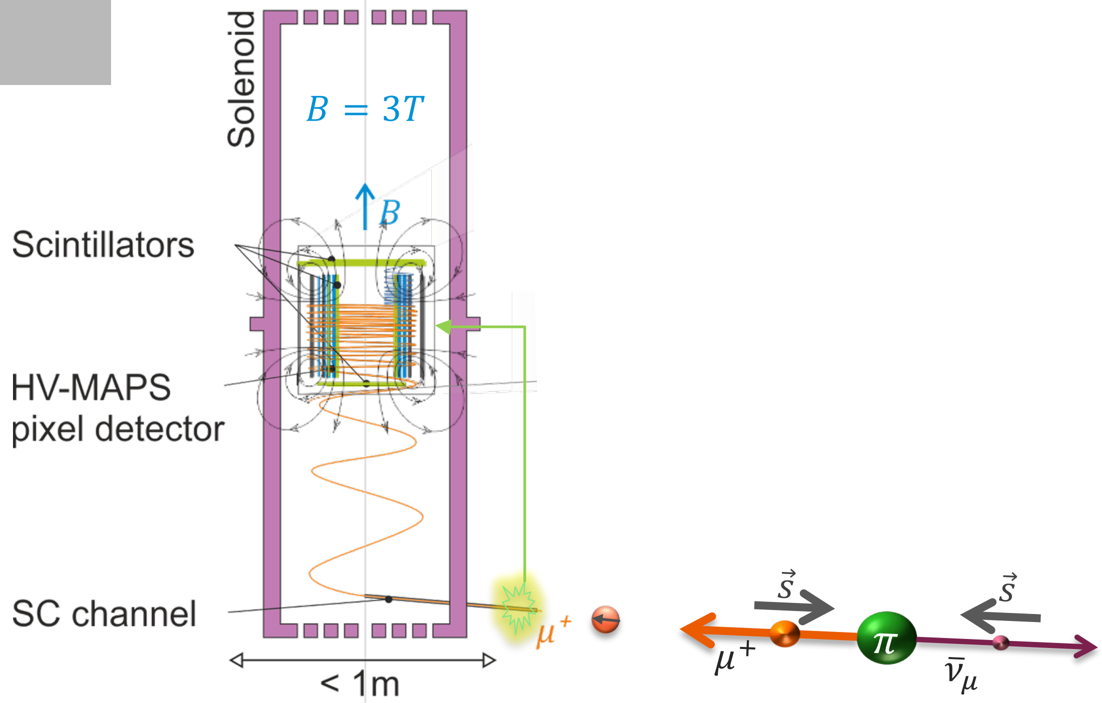
- Weak decay $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ results in decay asymmetry

$$\bar{\alpha} \approx 0.3$$

- Detection of e^+ of decay (for EDM vertical resolution)

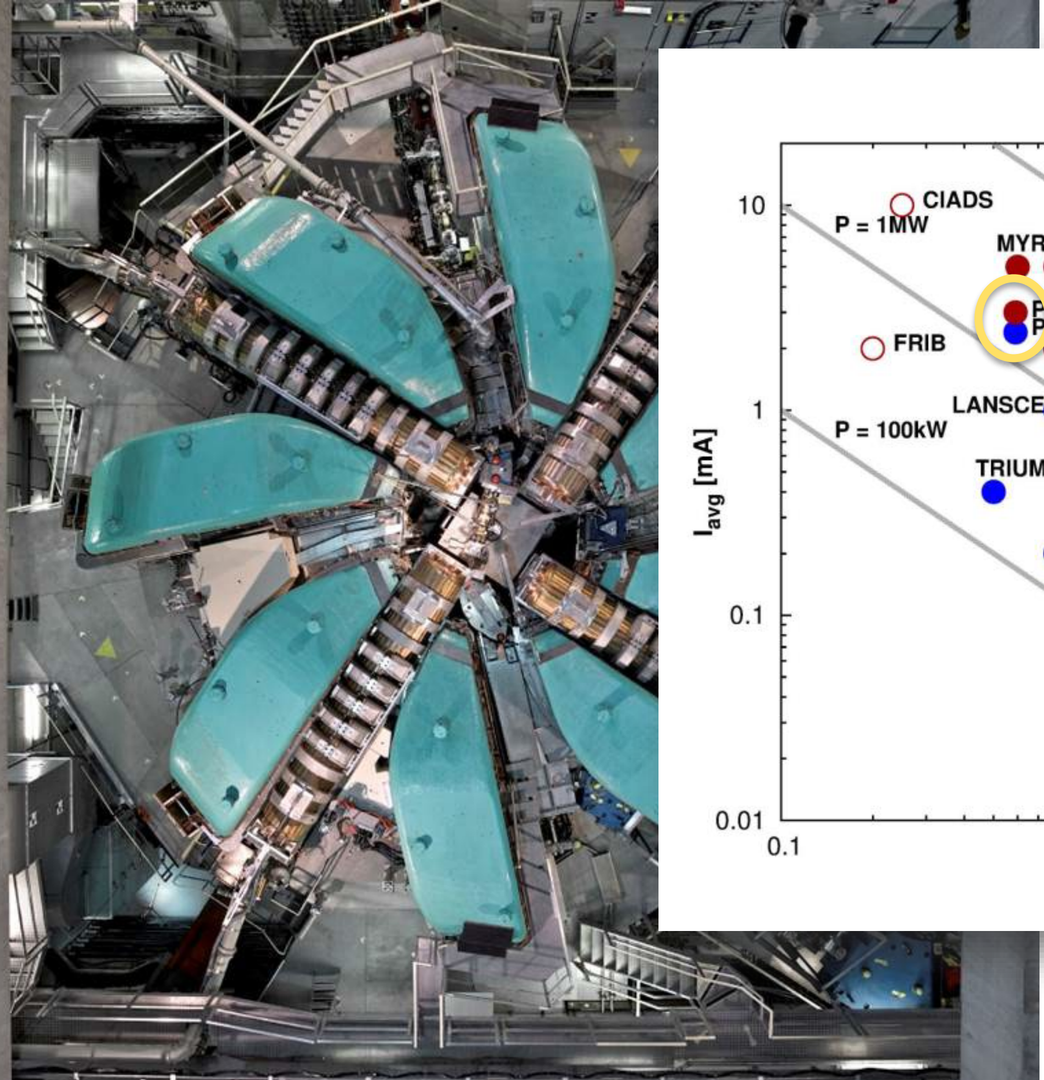


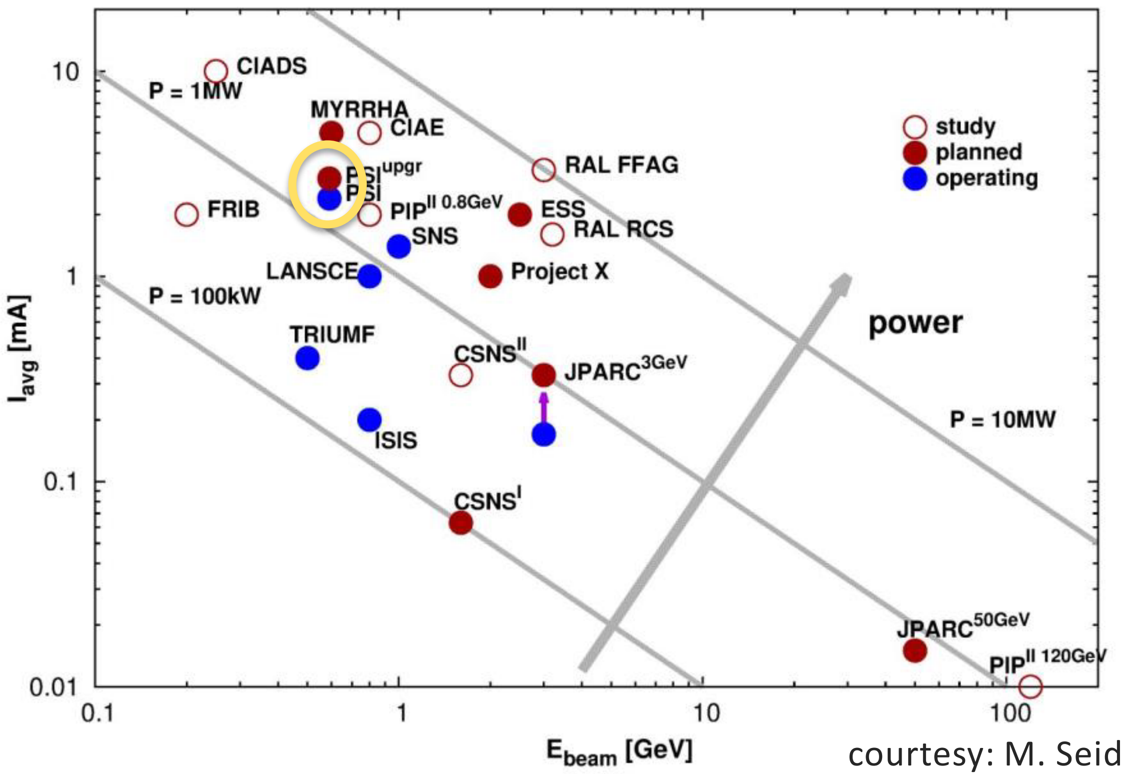
Search for a muon EDM using the frozen-spin technique with longitudinal injection



μ^+ @ $125\text{MeV}/c$ or $28\text{MeV}/c$

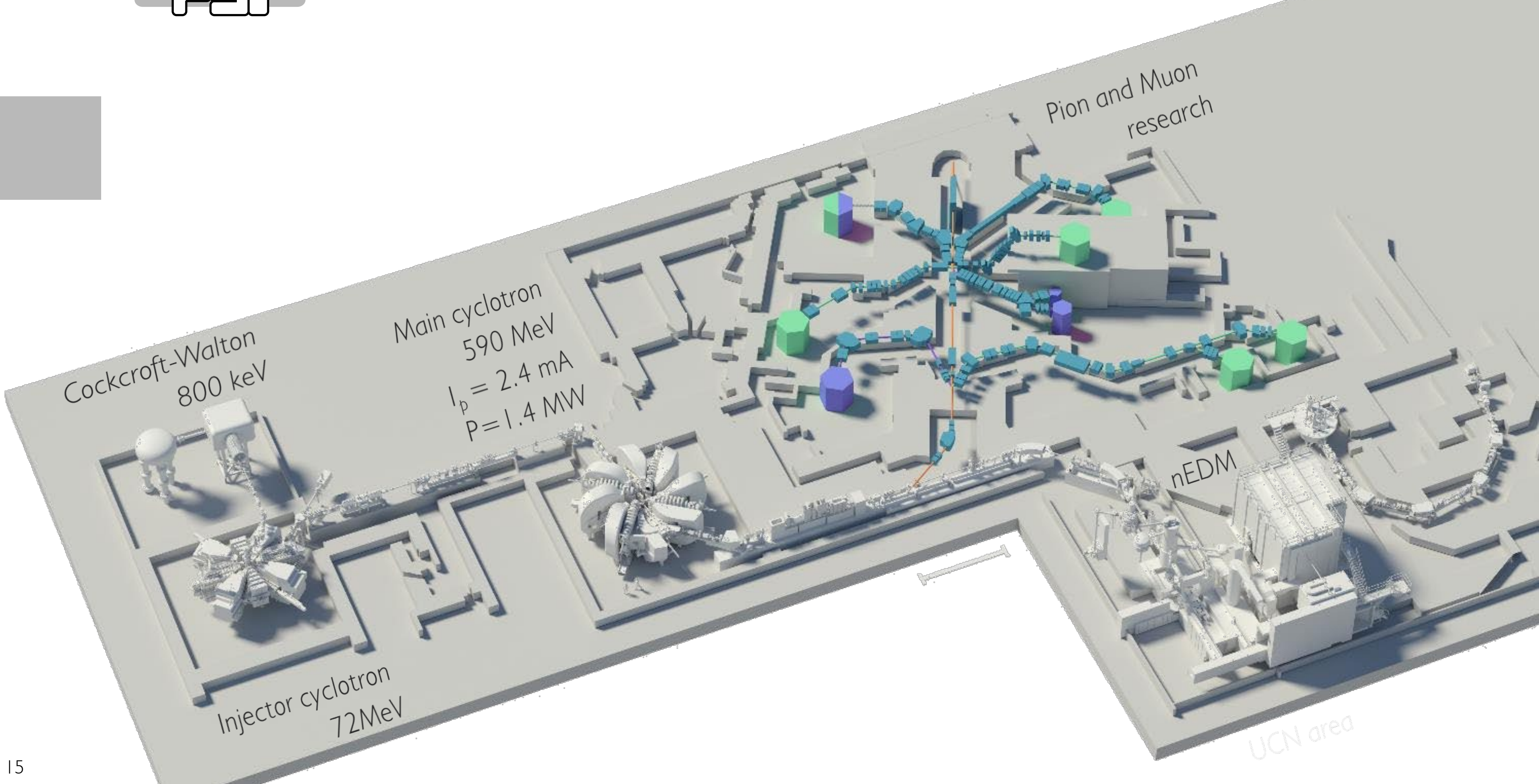
- μ^+ from **Pion-decay** $\rightarrow$ high polarization $p \approx 95\%$
- Injection through **superconducting channel**
- **Fast** scintillator **triggers** pulse
- Magnetic **pulse stops** longitudinal motion of μ^+
- Weakly focusing field for **storage**
- **Thin electrodes** provide electric field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



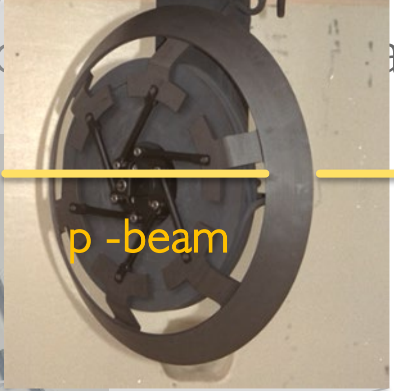


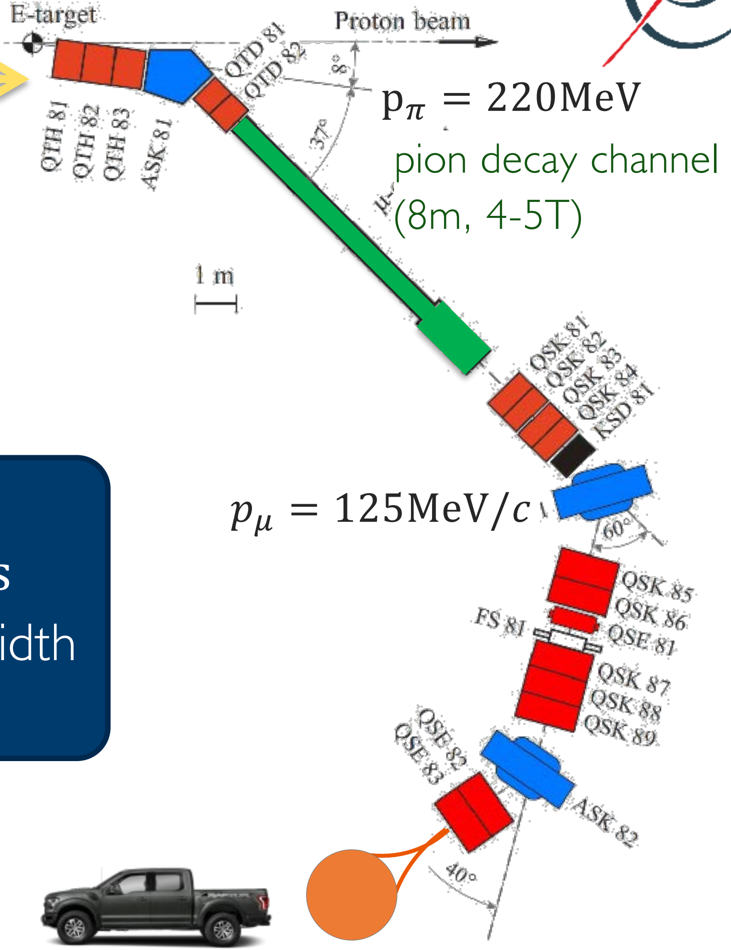
courtesy: M. Seidel

HIPA – High intensity proton accelerator



A searc at PSI





μ-beam:

- $10^8 \mu^+/s$
- Bunch width 3.9 ns

A phased approached

Phase I (small solenoid, surface muons)

- Existing solenoid at PSI, max 5T
- Bore diameters 200mm
- Field was measured in 2022 (found suitable for injection)

Phase 2 (dedicated magnet muon momentum $\geq 125\mathrm{MeV}/c$)

- Large bore (up to 900 mm diameter)
- High Temporal field stability (10ppb/h)
- Excellent spatial field uniformity (< 1 ppb/mm)

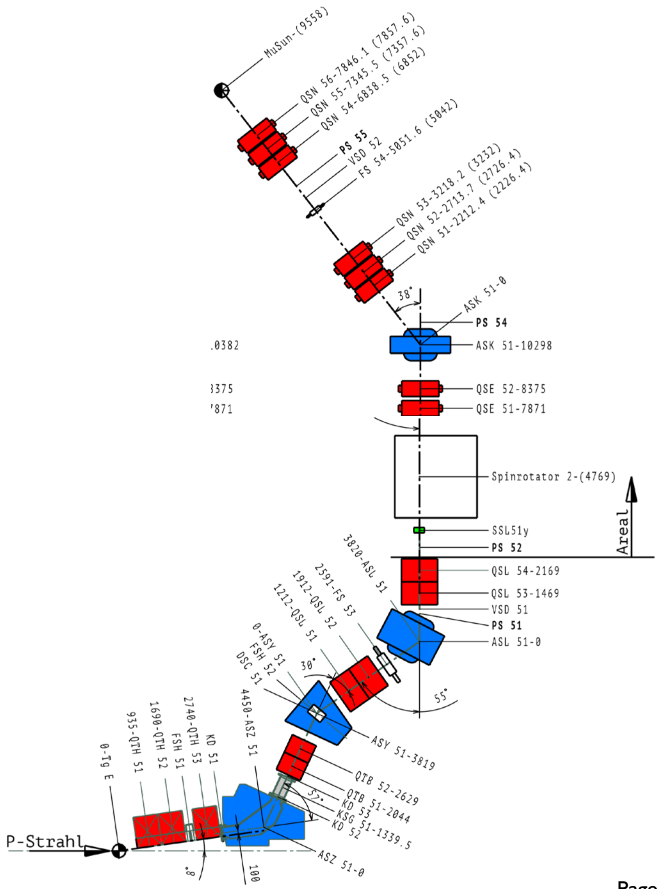
Surface muons for phase-I

Horizontal Emittance: $200\ \pi\text{mm mrad}$

Vertical Emittance: $170\ \pi\ \text{mm mrad}$

- Beam rate about $4 \times 10^6\ \text{s}^{-1}$
- Acceptance phase space:
  - High transmission through channel 3%
  - Injection efficiency about 2%
  - Expected μ^+ storage rate 2kHz
  - Expected e^+ detection rate 0.5kHz

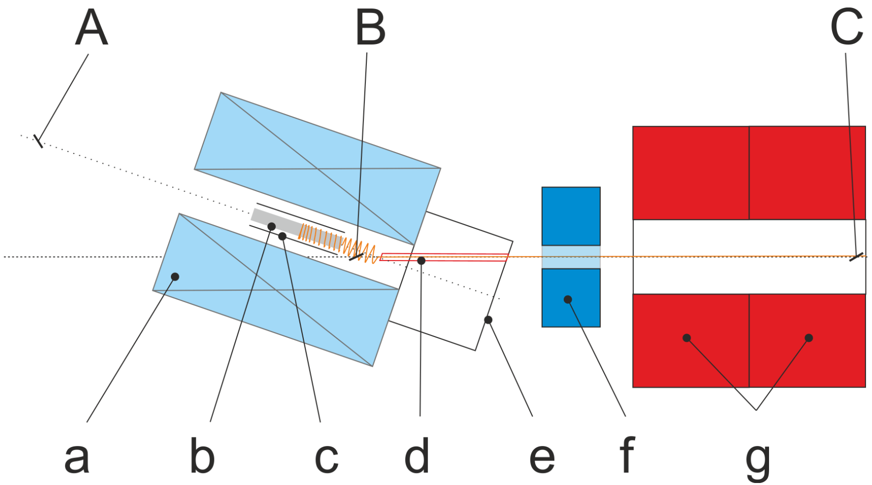
- Moderate E field 3kV/cm



Injection and statistical sensitivity

- Large phase space at exit of beam collimated by passage through a collimation channel (d)
- Due to adiabatic magnetic collimation large part of transmitted μ^+ are reflected.
- Simulations show, only about 0.5×10^{-3} muons can be stored

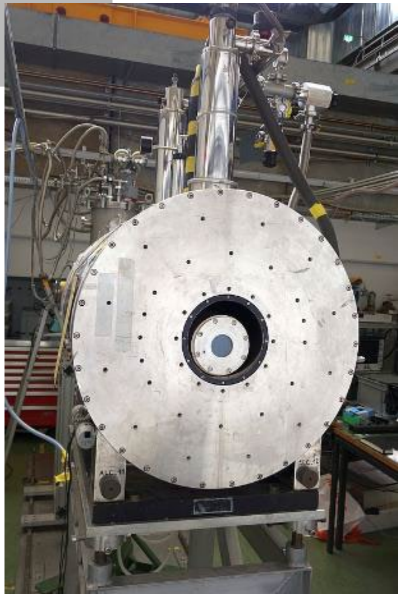
$$\sigma(d_\mu) = \frac{\hbar \gamma a_\mu}{2pE_f\sqrt{N}\,\tau_\mu\,\alpha}$$

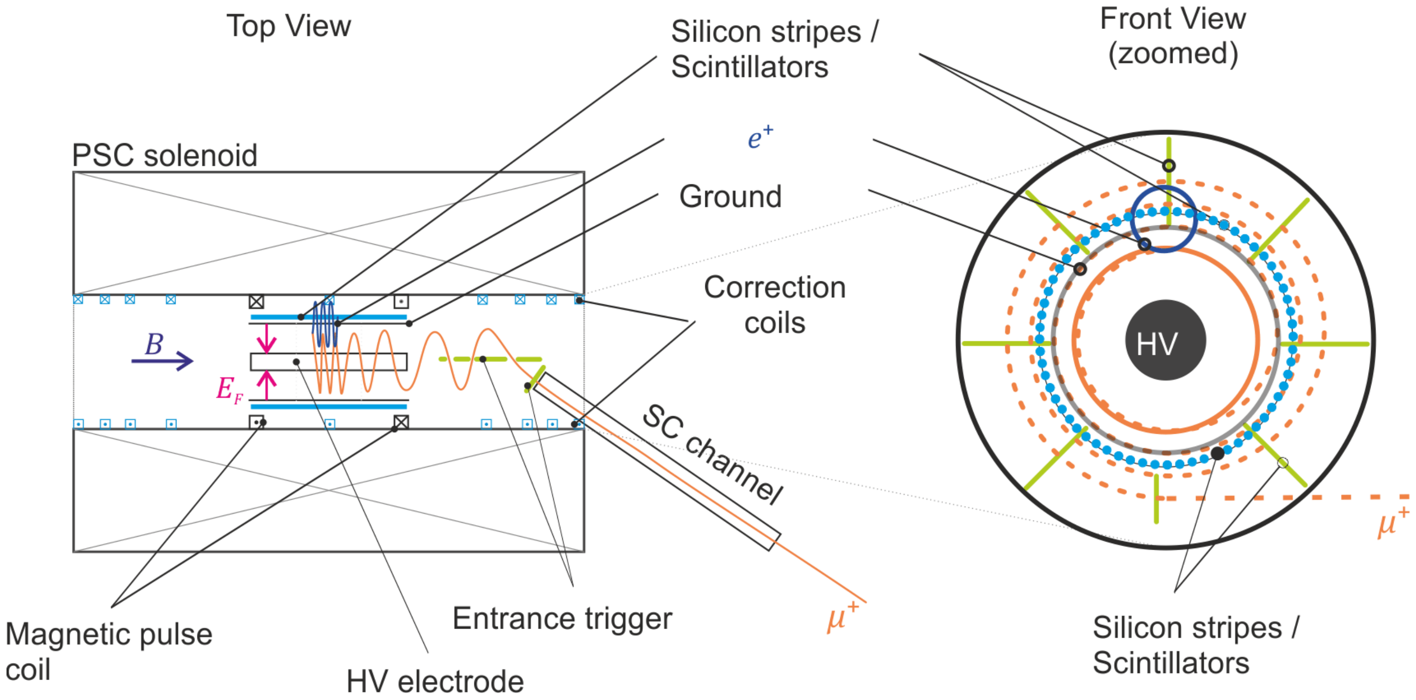


	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.017	0.60
Muon storage rate (1/s)	2×10^3	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	500	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.3	0.3
Initial polarization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

The muEDM phase I on piE1

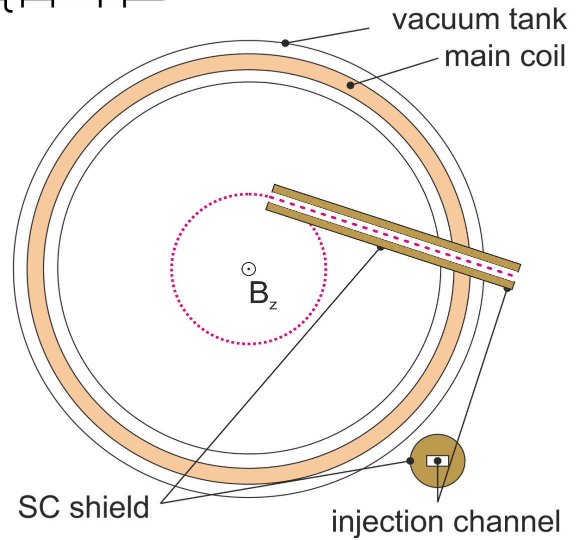
Test bed and frozen spin demonstrator



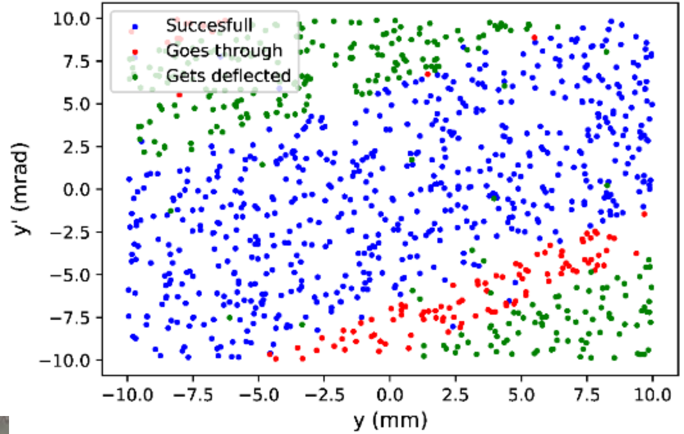


muEDM measurement $< 3 \cdot 10^{-21} ecm$

Injection channel

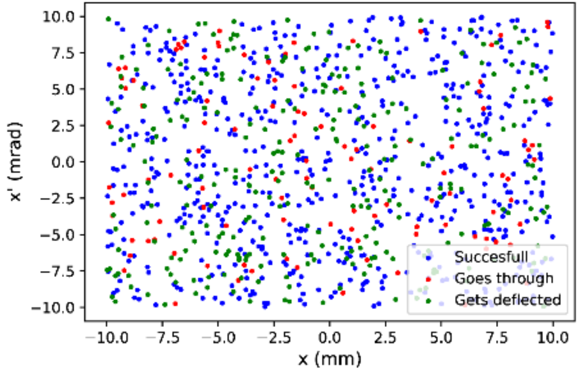


- Injection channel with SC magnetic shield
- Defines vertical and horizontal divergence



vertical

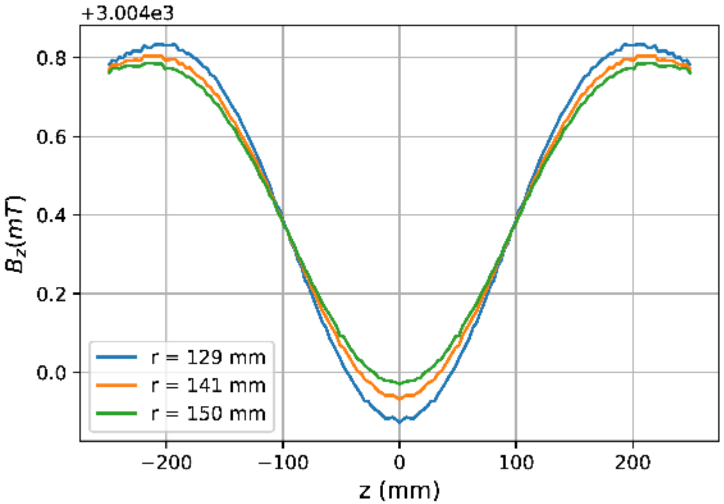
horizontal

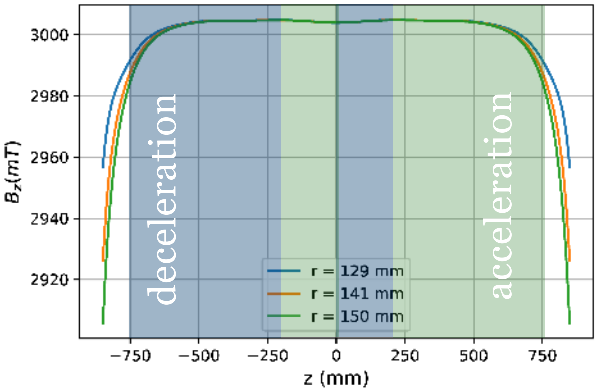


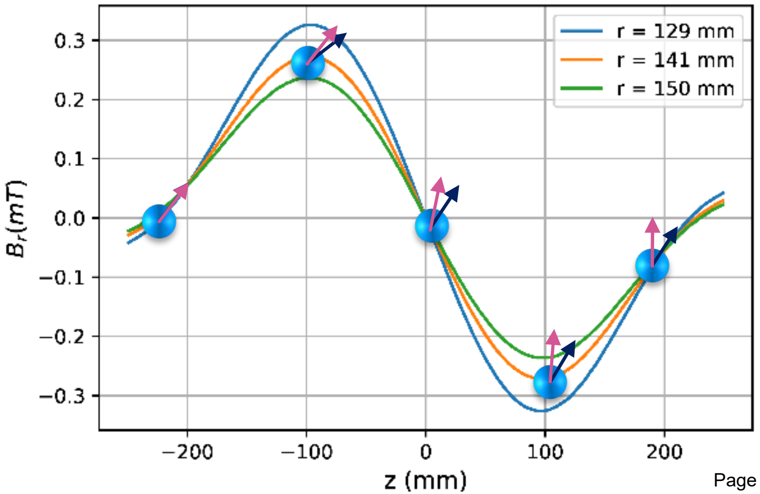
D. Barna et al., PR Acc. B 20 (2017) 041002
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4900108.
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4101310.

Storage and injection

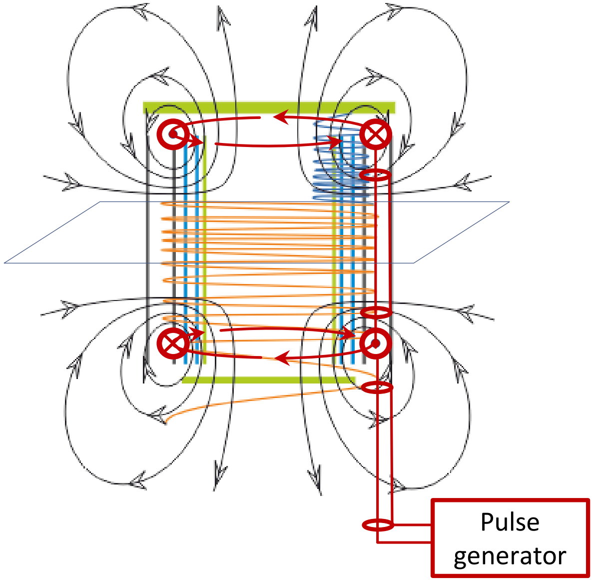
- Strength of weakly focusing field in the center region defines "depth" of storage
- The deeper / stronger the weakly focusing field the stronger needs to be the pulse

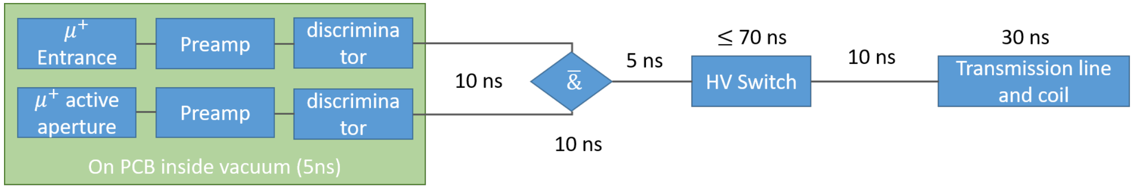


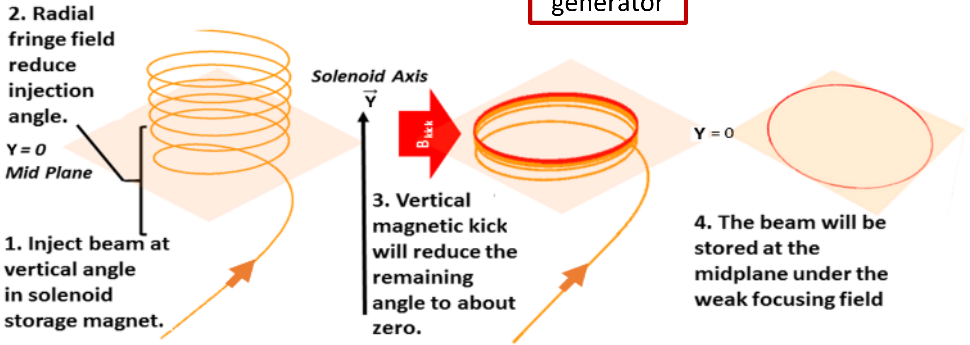


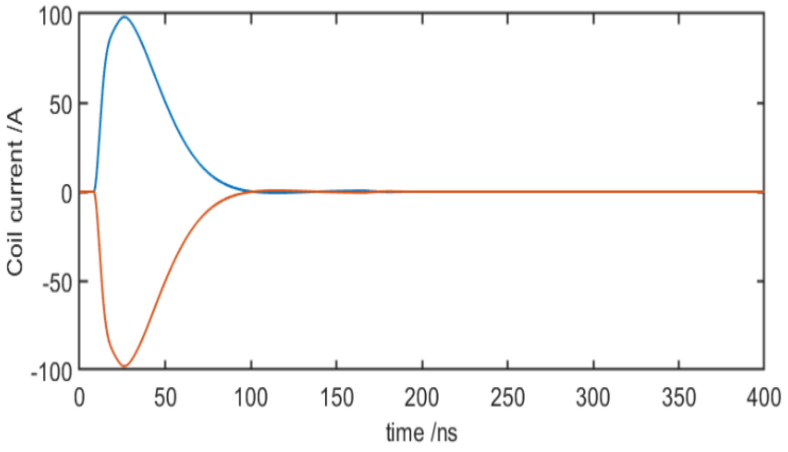


Radial magnetic field pulse to kick muons









courtesy A.M. Rehman

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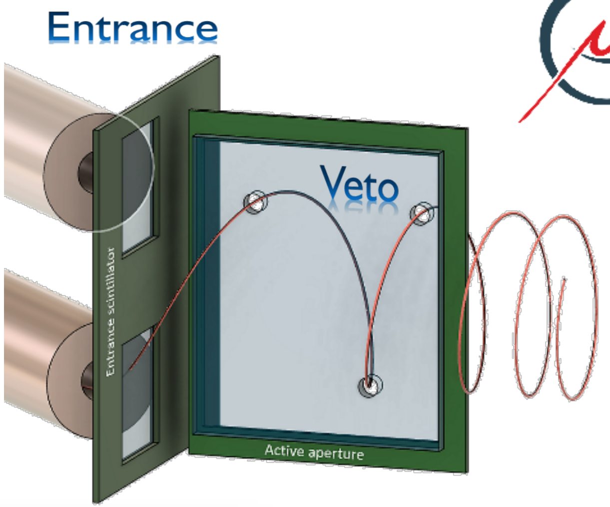
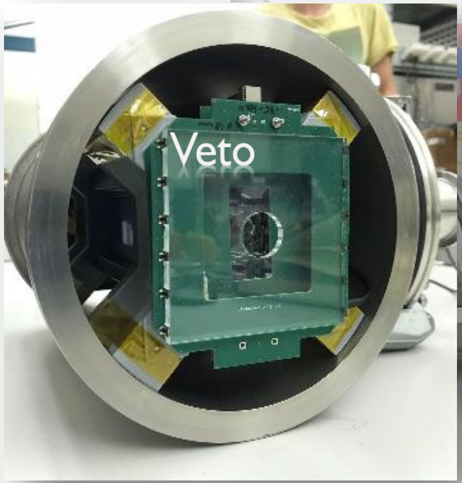
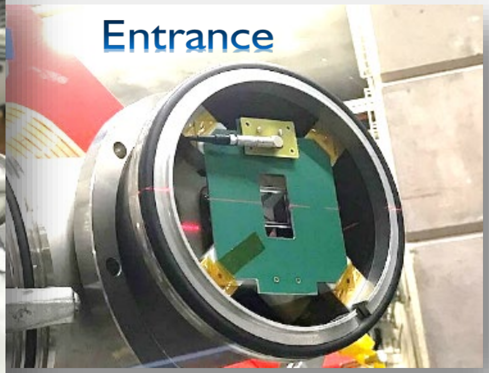
Muon entrance trigger

- Magnetic pulse needs to be triggered by incident muon
- Only about 2% of muons passing through the collimation channel are within the acceptance phase space
- Scattering in scintillators increase beam divergence

- Combine thin ($\leq 100\mu m$) entrance scintillator with
- Active aperture as veto





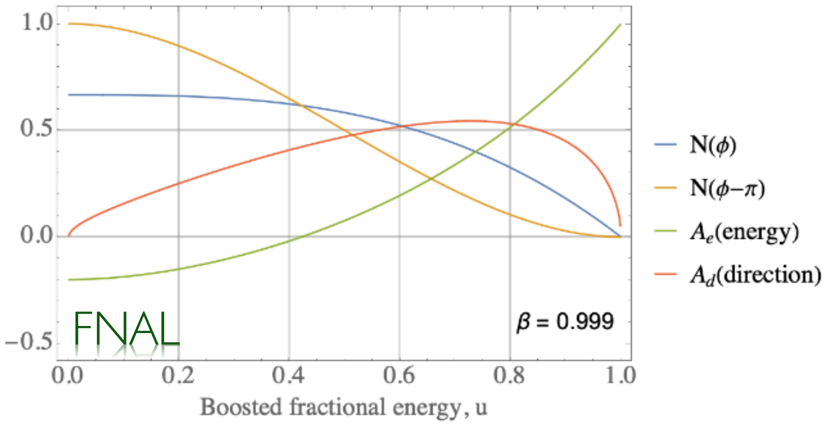


Positron detection – figure of merit

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

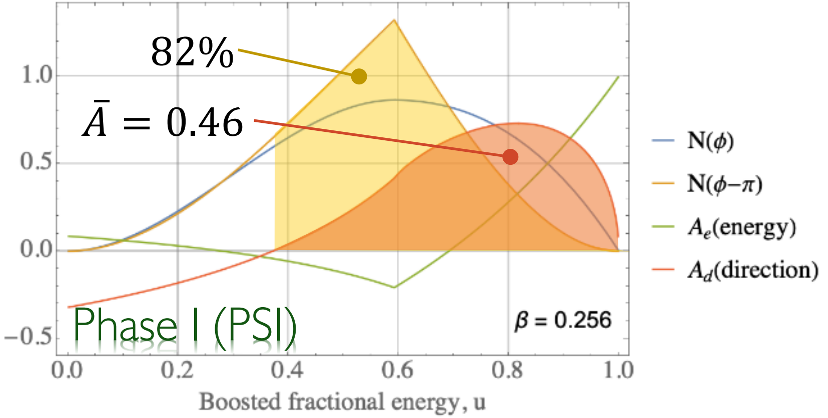
Requires momentum resolution



Detection of EDM polarization

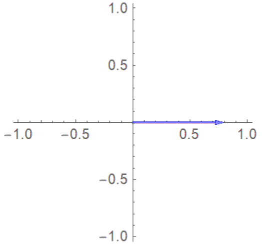
- Measurement of Asymmetry as function of time $A(t)$

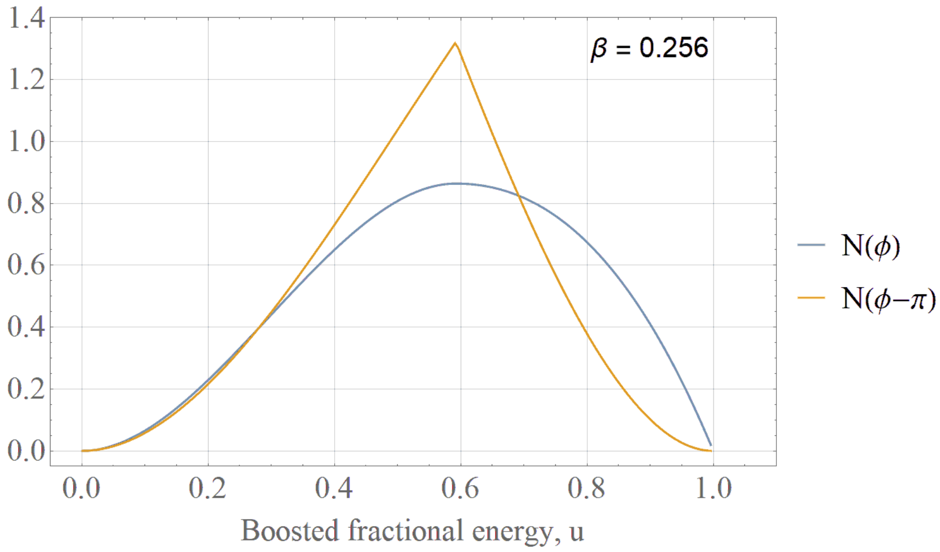
Requires spatial resolution along cylinder



Tuning the electric field to the frozen-spin condition

- Measure the g-2 frequency ω_a
- Two momentum bins
  $28\ \mathrm{MeV}/c < p_1 < 50\mathrm{MeV}/c$
  $50\ \mathrm{MeV}/c < p_2$
- Change E field in the range
  $\pm E_{\mathrm{frozen}} \approx \pm 3\mathrm{kV/cm}$
- Extrapolate to E_{frozen} where $\omega_a = 0$

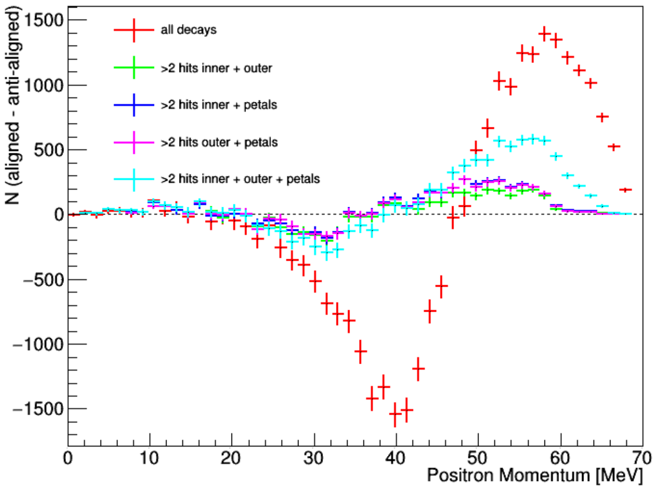


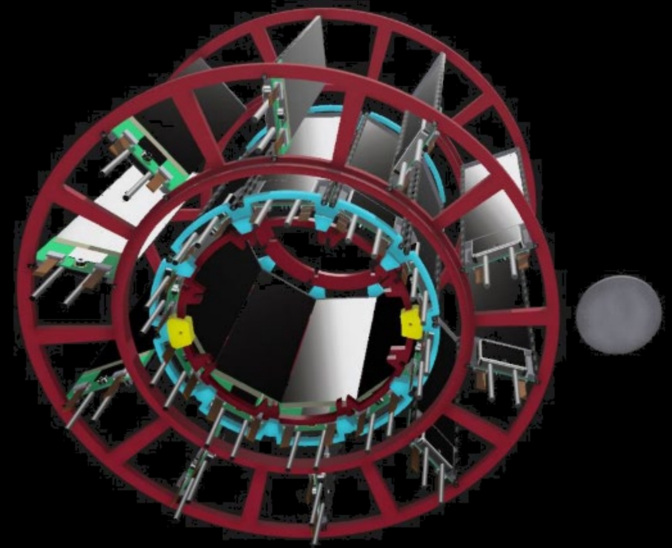


Silicon strip detector for g-2 detection

Silicon strip detector for g-2 detection

- Reconstruction of transverse positron momentum ($\Delta p \approx 5\mathrm{MeV/c}$)
- Timing $\Delta t \approx 2\mathrm{ns}$
- Spatial resolution $\approx 0.1\mathrm{mm}$ (lateral)



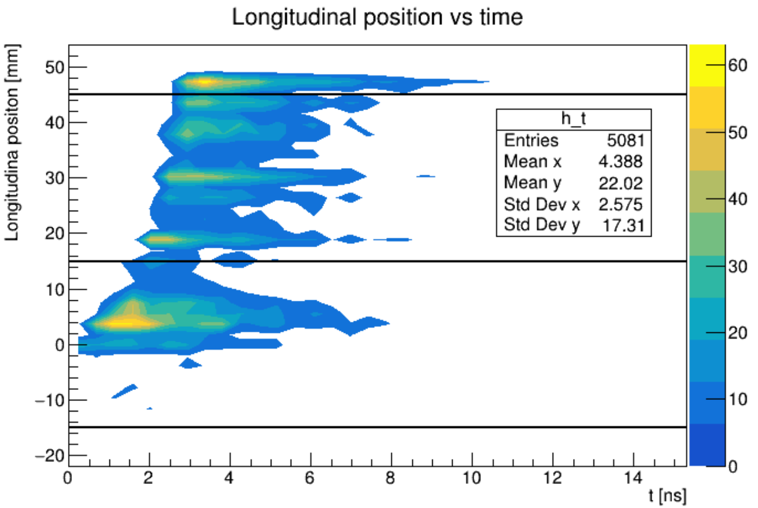


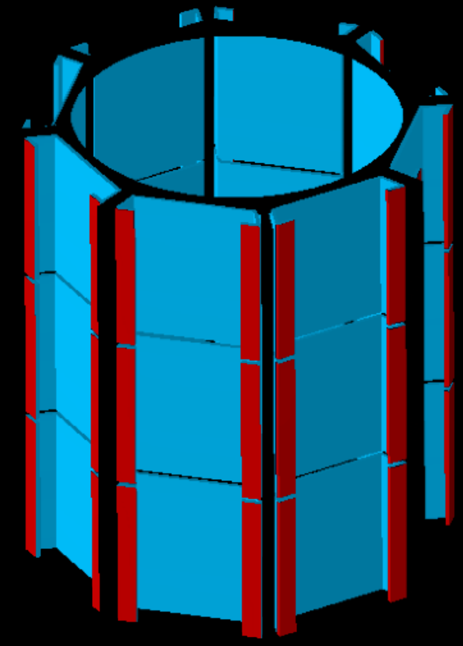
Si-Petal detector

Scintillating fiber detector for EDM-signal

Scintillating fiber detector for EDM asymmetry measurement and timing

- Horizontal fiber ribbons with $250\mu m$ pitch and $100\mu m$ resolution
- Timing resolution $< 2ns$
- Reconstruction of longitudinal momentum





SciFi-EDM detector

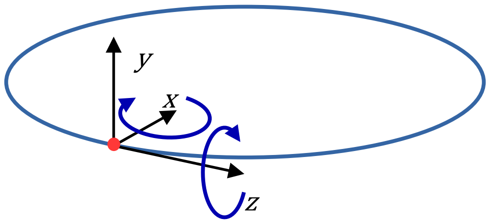
Systematic studies (example)

- Systematic effects: all effects that lead to a *real* or *apparent* precession of the spin around the radial axis that are not related to the EDM

- Major sources of systematic effects in the frozen spin technique:
  - Coupling of the magnetic moment with the EM fields of the experimental setup (*real*)
  - Early to late variation of detection efficiency of the EDM detectors (*apparent*)

- **Rotations that could mimic the EDM:**
  - **Radial around x**
  - **Azimutal around z**

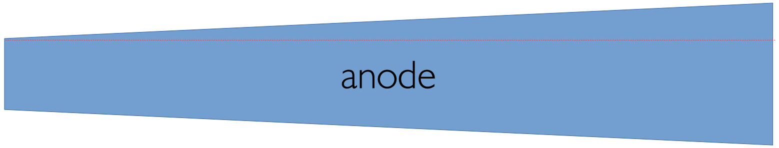
$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$



Sources of E_y field: conical central electrode

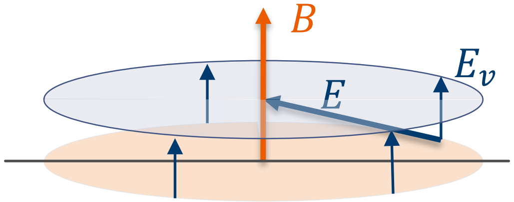
- None constant radius of cylindrical anode (cone)

$$E_y \approx E_f \frac{\Delta_R}{L} \approx E_f \alpha$$



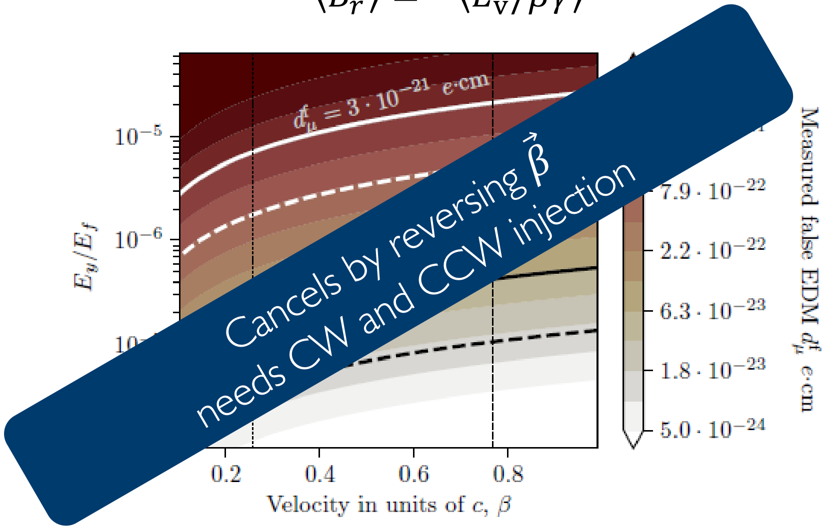
- Cylindricity on the order of 50 nm is measurable even on large samples and possible to machine

- Ground electrode made of thin foil more difficult to keep deviations from cylindricity below **30μm**

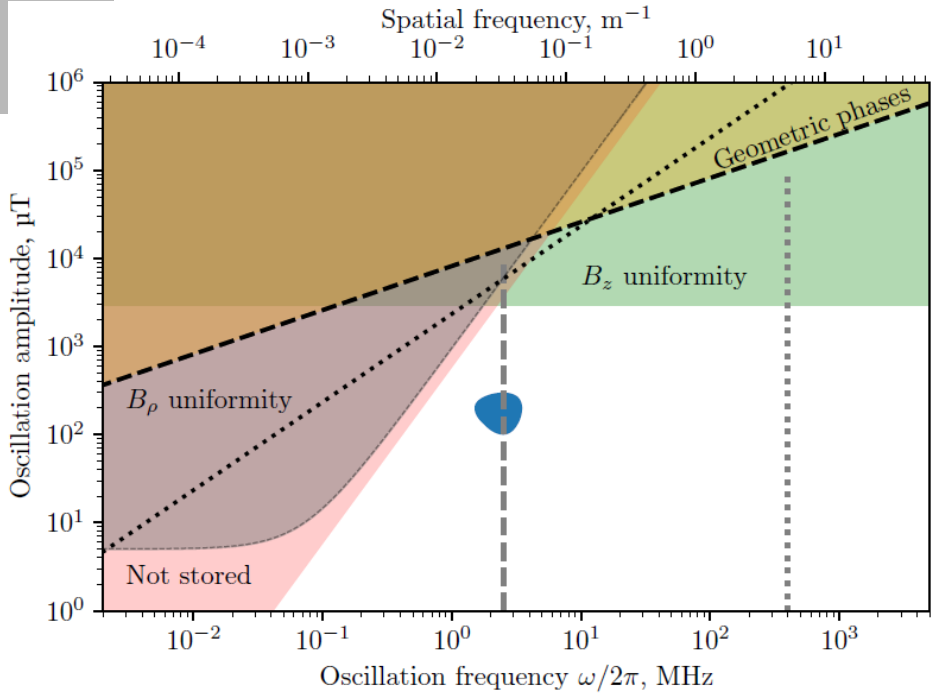


Will move orbit out of central plane until:

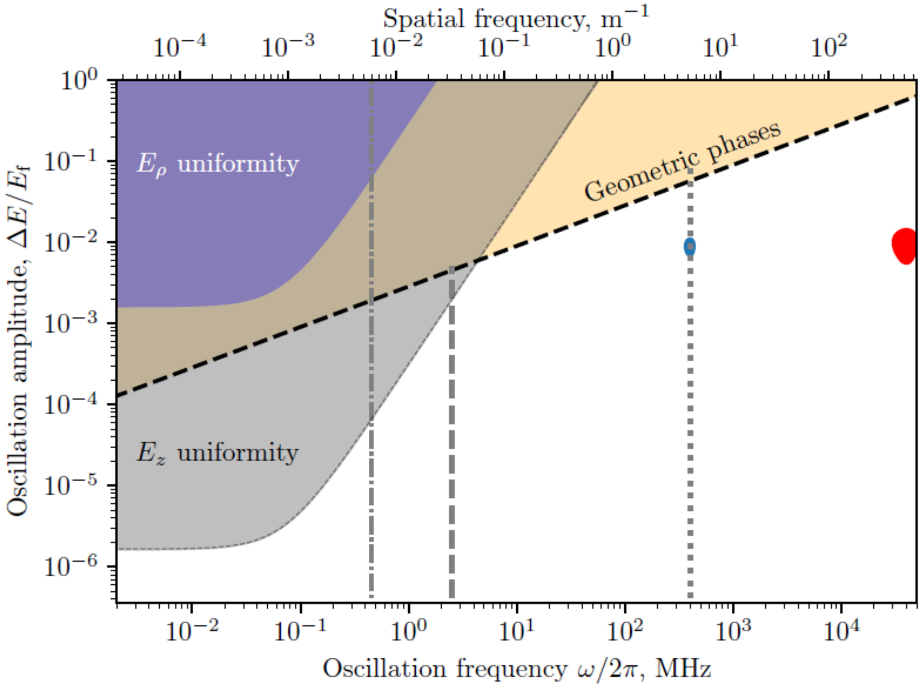
$$\langle B_r^* \rangle = -\langle E_\text{v}/\beta\gamma \rangle$$



Geometric phases, and non-uniformities



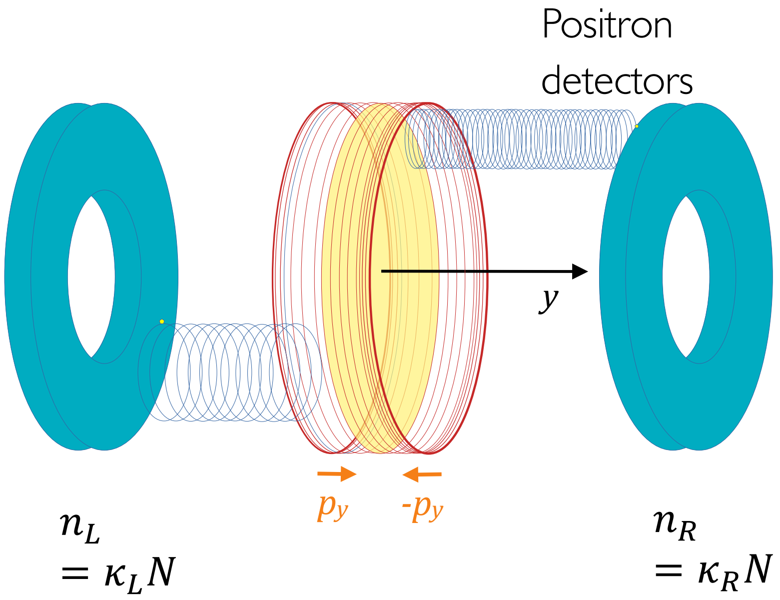
Magnetic field



Electric field

Detection efficiency asymmetry

- The EDM will be deduced from the accumulation of asymmetry between the upstream and downstream detectors that increases with time
- Static differences in the detection efficiency of one detector compared to the other is not a problem
- Change of the detection efficiency with time is a problem as it will introduce time dependent asymmetry



Constraints on the total detection efficiency

- Assumption: Change of detection efficiency triggered by pulse, exponential decay

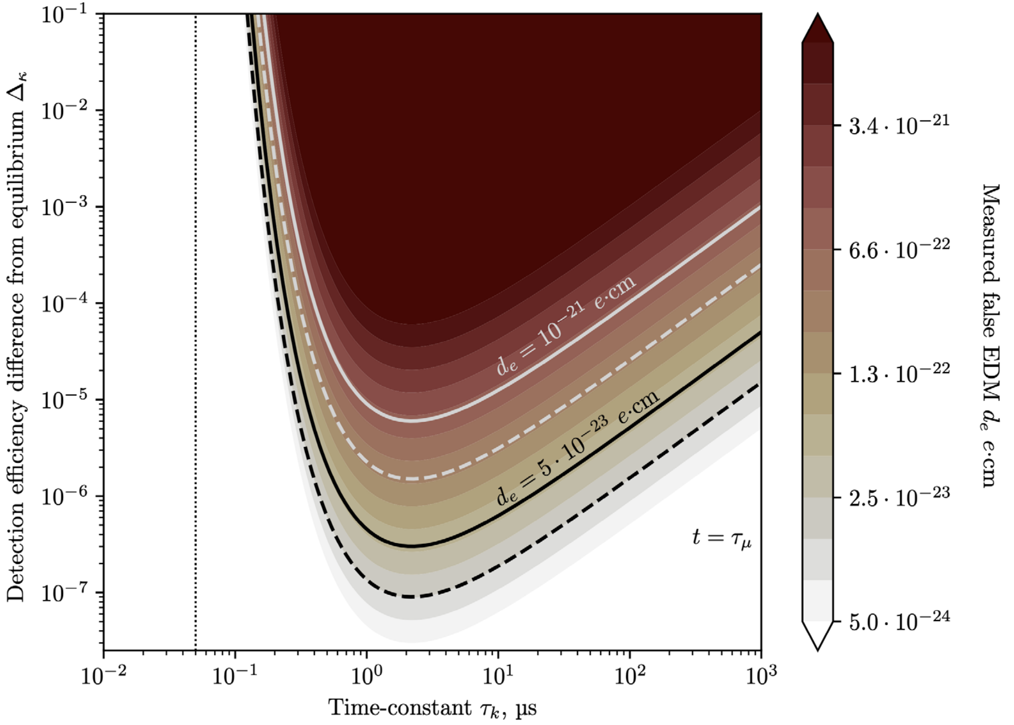
- Detection efficiency of up and downstream detectors:

$$\kappa_u = \kappa_{u0} - \Delta_\kappa e^{-t/\tau_k},$$

$$\kappa_d = \kappa_{d0} + \Delta_\kappa e^{-t/\tau_k},$$

- Change in measured asymmetry with time:

$$\dot{A}_m = \frac{2}{\tau_k}\Delta_\kappa e^{-t/\tau_k}$$



Systematic study - overview

- Systematic effects are studied using analytic expressions
- Comparison with GEANT4 spin tracking Monte Carlo for verification
- Deduce specifications for experiment

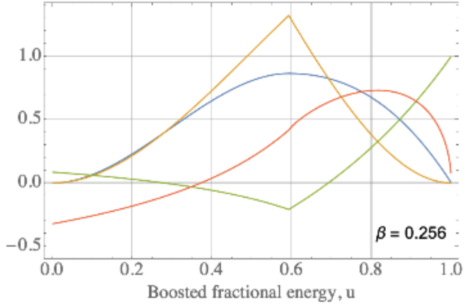
Next steps:
- Parametrization of magnetic-field non-uniformity
- Deduce magnetic-field requirements

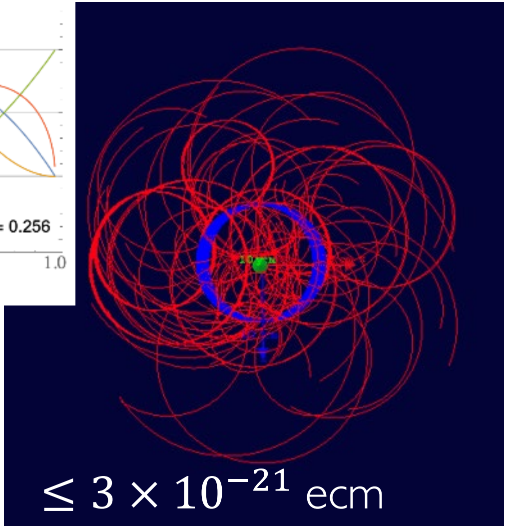
Systematic effect	Constraints	Phase I	
		Expected value	Syst. ($\times 10^{-21}$ e·cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ µm	0.75
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$
Net current flowing muon orbit 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

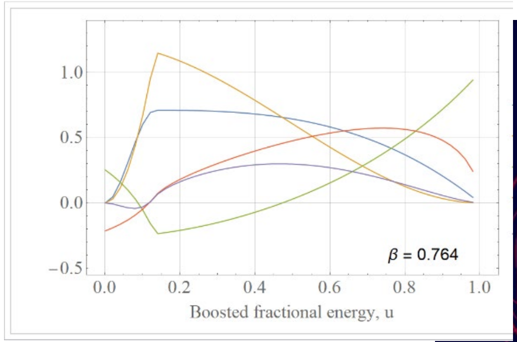
Going from phase I to phase II

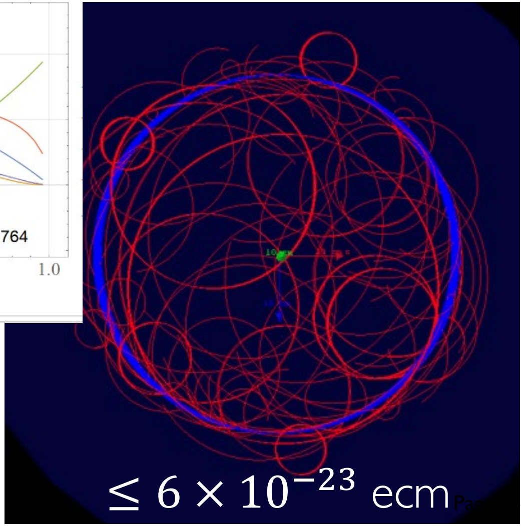
Phase I
- B-Field 3T
- Momentum 28 MeV/c
- Muon radius 31mm
- Most positrons outside

Phase II
- B-Field 3T
- Momentum 125 MeV/c
- Muon radius 141 mm
- Most positrons inside









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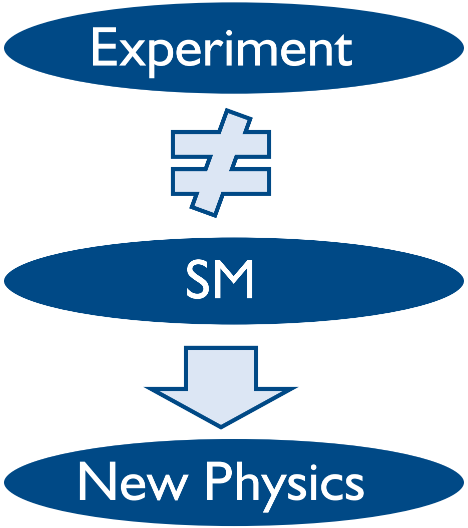
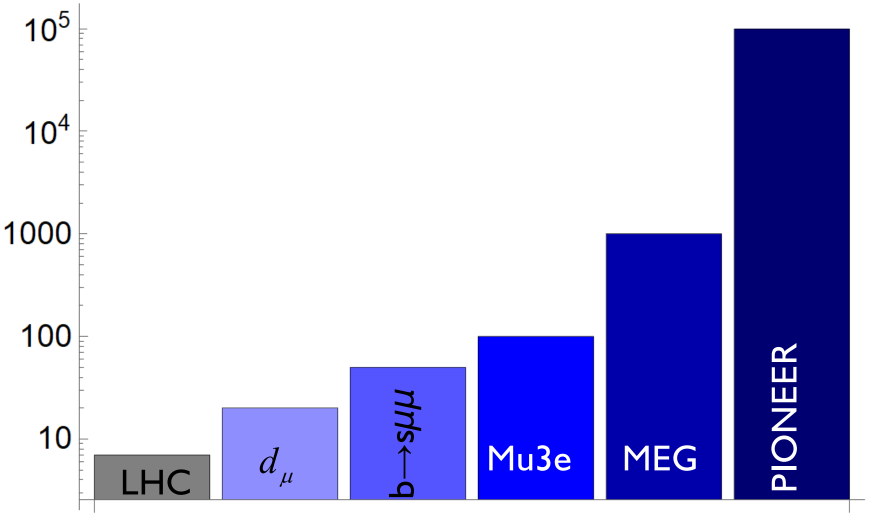
PAUL SCHERRER INSTITUT

Backup

Finding New Physics with Flavor

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

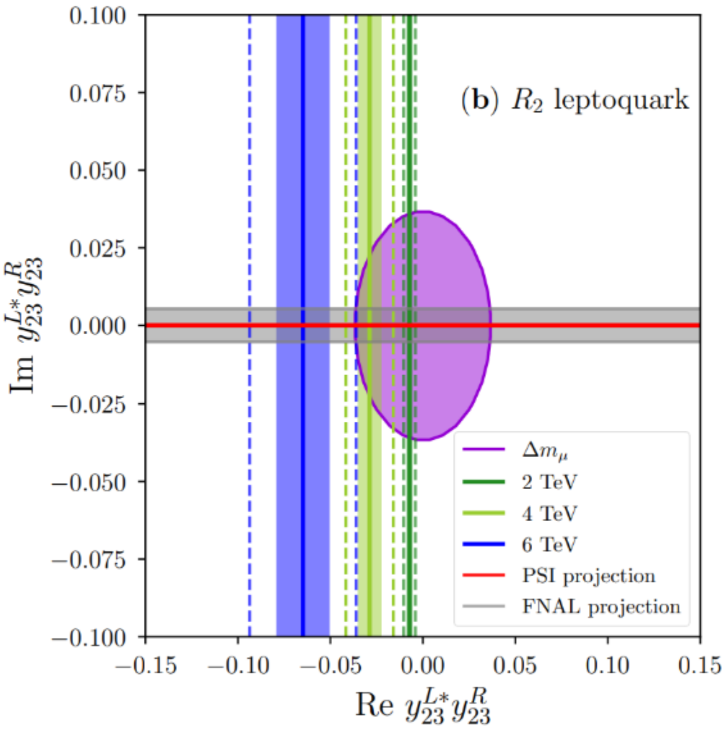




Flavor observables are sensitive to higher energy scales than collider searches

Courtesy Andreas Crivellin

Fine-Tuning?

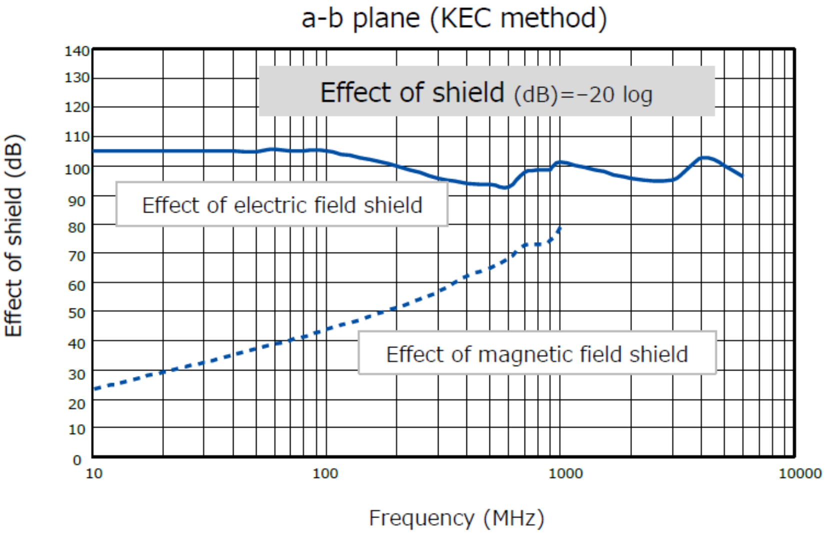


Bigaran, Volkas, 2110.03707

No signifcant tuning necessary

Courtesy Andreas Crivellin

Eddy current damping of magnetic pulse



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

Multiple scattering measurement on carbon

- Characterization of potential electrode material with positrons and muons

$$50\ \mathrm{MeV}/c < p < 145\ \mathrm{MeV}/c$$