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Systematic effects in the muEDM experiment at PSI

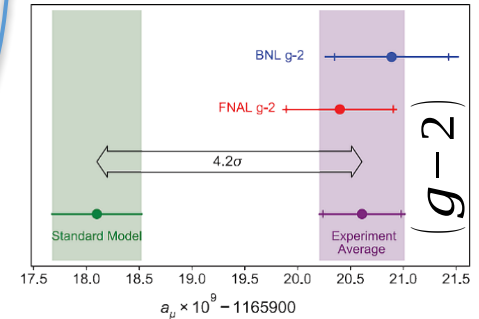
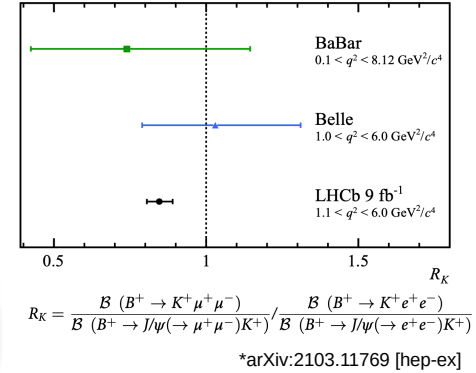
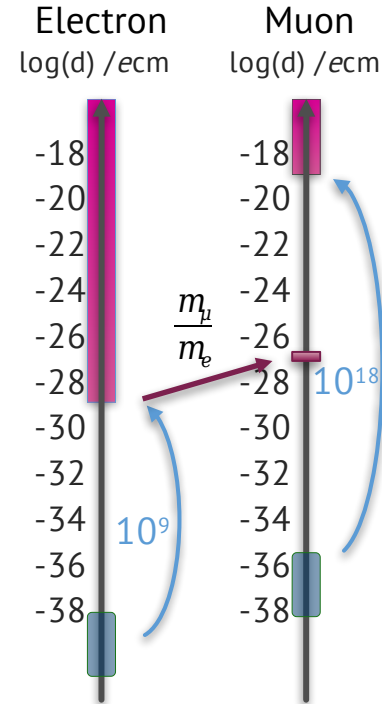
On behalf of the muonEDM collaboration

Motivation for EDM searches

- Electric dipole moments of fundamental particles are widely recognized as unique probes for New Physics
- A permanent EDM violates P, T and assuming CPT conservation, also CP
 - Required to explain the observed baryon asymmetry in the Universe (under CPT conservation and symmetric initial conditions)
- Standard Model predictions for EDMs are orders of magnitude below current sensitivity of experiments
 - Negligible background from Standard Model physics
 - Observation of non-zero EDM would be a clear sign of new physics

EDM of the muon

- The current experimental limit on the muon EDM is $\sim 10^{-19} \text{ ecm}^*$
- Assuming minimum flavour violation, lepton flavour universality and naive mass scaling of the electron EDM one can place a 10^{-27} limit on the muon EDM
- Tensions in semi-leptonic B decays at LHCb, Belle and BaBar challenge these assumptions
- Combined with the long-standing muon (g-2) tension there are strong hints of New Physics involving the muon

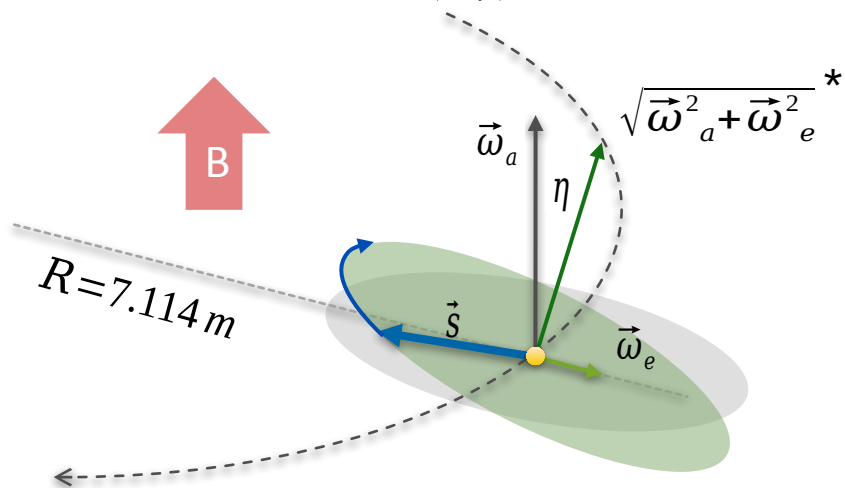


*Bennet et al. PhysRevD.73.072003 (2006)

Sensitivity from (g-2) experiments

$$\vec{\Omega} = -\frac{e}{m_0} \left[\underbrace{a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right)}_{\text{EDM term}} \right]$$

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



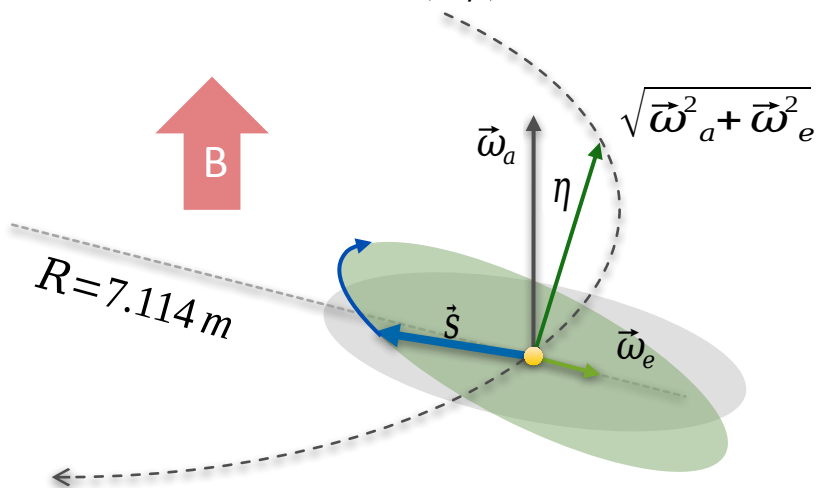
*Chislett, R.EPJ Web Conf., (2016) 118, 01005, **Abe et al., PTEP053C02 (2019)

The frozen spin technique*

$$\vec{\Omega} = -\frac{e}{m_0} \left[\underbrace{a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right)}_{\text{EDM term}} \right]$$

FNAL & JPARC

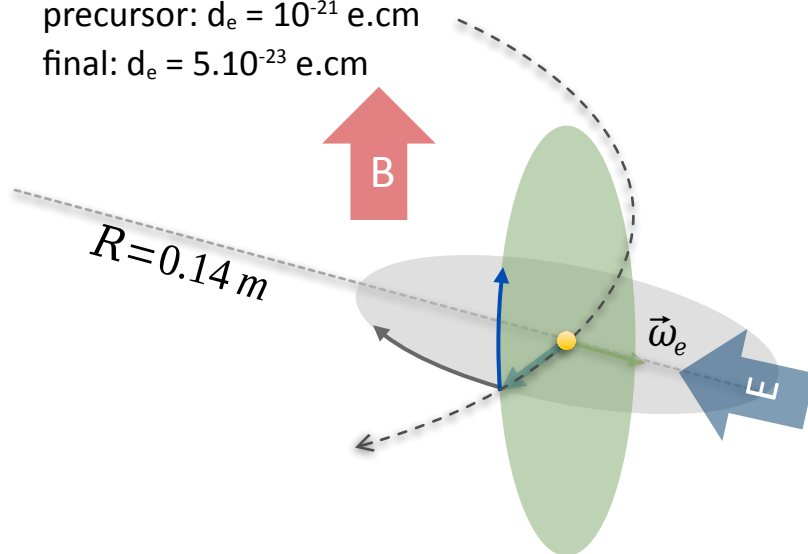
$$\sigma(d_\mu) \approx 10^{-21} \text{ ecm}$$



Frozen spin at PSI:

precursor: $d_e = 10^{-21} \text{ e.cm}$

final: $d_e = 5 \cdot 10^{-23} \text{ e.cm}$



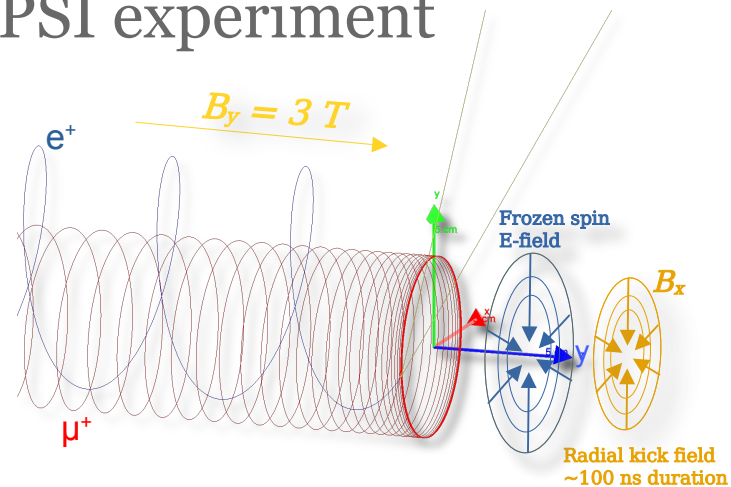
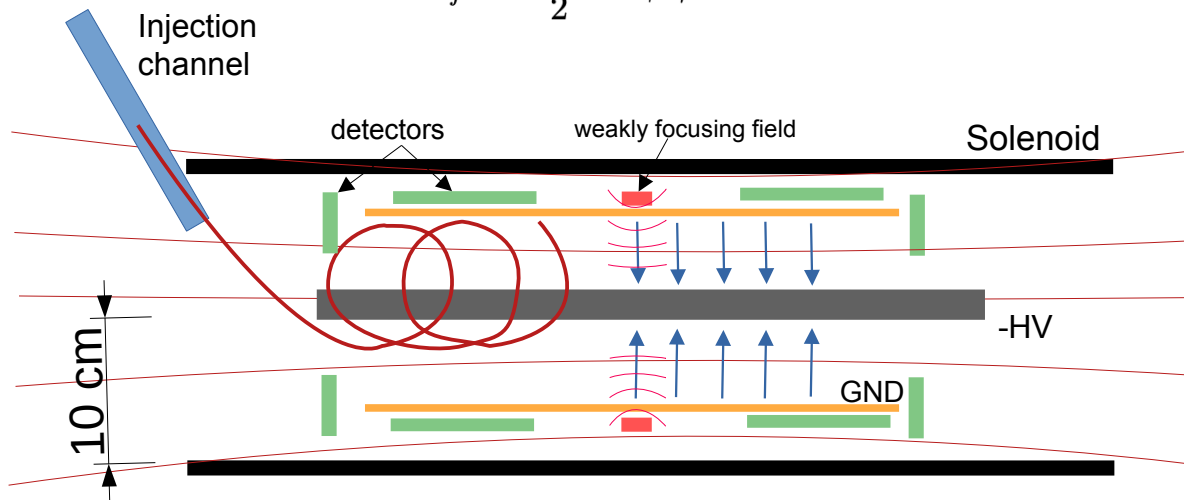
*Farley et al, PRL93 042001 (2004)

Search for the muon EDM using the frozen spin technique at PSI

Main components of the PSI experiment

- 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

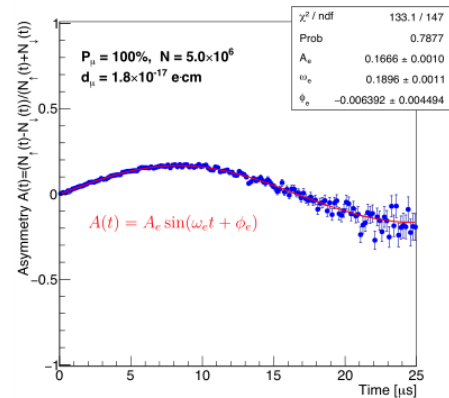
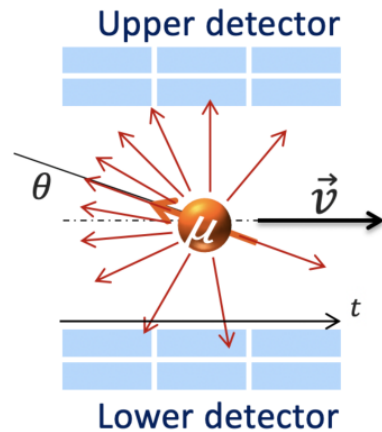
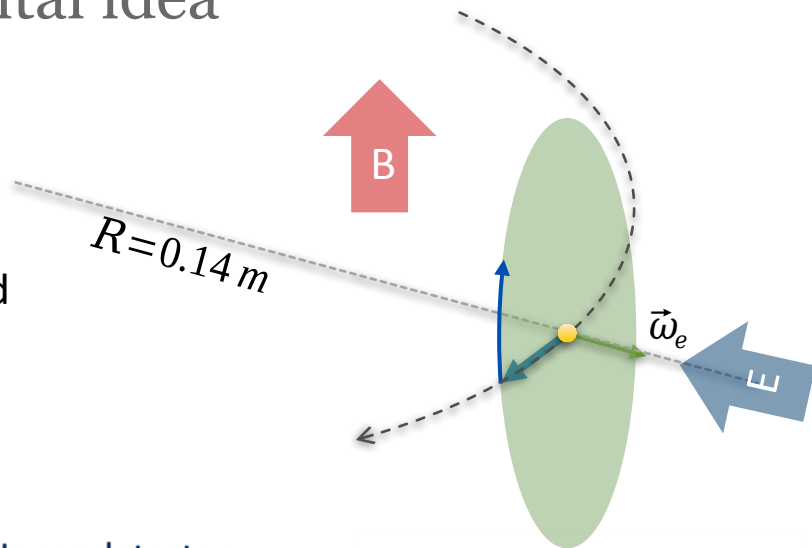
$$E_f \approx \frac{g-2}{2} B c \beta \gamma^2$$



- The observable of interest is the asymmetry between 'upstream' and 'downstream' detectors as a function of time

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 in the direction of emitted positrons will be observed
- 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**



- 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
- The work by Farley et al. used as a starting point:

VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending
30 JULY 2004

New Method of Measuring Electric Dipole Moments in Storage Rings

F. J. M. Farley,⁷ K. Jungmann,⁴ J. P. Miller,² W. M. Morse,³ Y. F. Orlov,⁵ B. L. Roberts,² Y. K. Semertzidis,³
 A. Silenko,¹ and E. J. Stephenson⁶

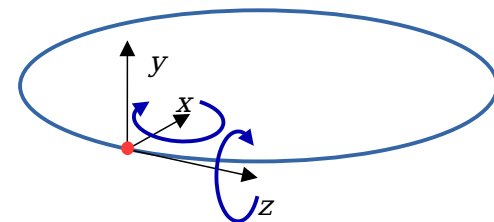
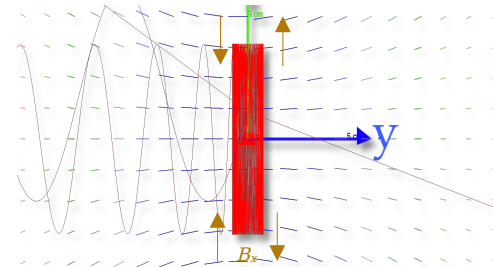
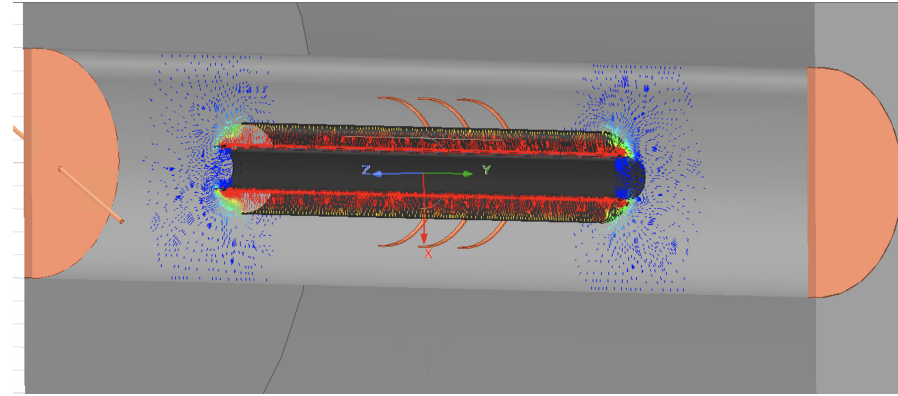
- Major sources of systematic effects in the frozen spin technique:
 - Early to late variation of detection efficiency of the EDM detectors (apparent)
 - Coupling of the anomalous magnetic moment with the EM fields of the experimental setup (real)

A solid grey square is positioned to the left of the title text.

Systematic effects related to real spin precession

Coupling of the MDM to EM fields

- Main EM fields in the experiment:
 - Main solenoid
 - Coaxial electric freeze field
 - Weakly focusing field
 - Magnetic kick (time varying)
- Rotations that could mimic the EDM:
 - Radial around x
 - Azimutal around z

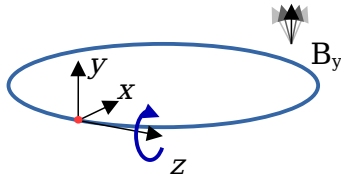


$$\vec{\Omega}_{\text{MDM}} = -\frac{e}{m_0} \left[a\vec{B} - a\frac{\gamma-1}{\gamma} \frac{(\vec{\beta} \cdot \vec{B})\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

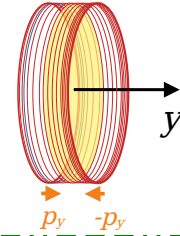
Oscillating and constant terms

- Using the T-BMT equation one can describe analytically the spin precession due to the MDM in the EM fields of the experiment

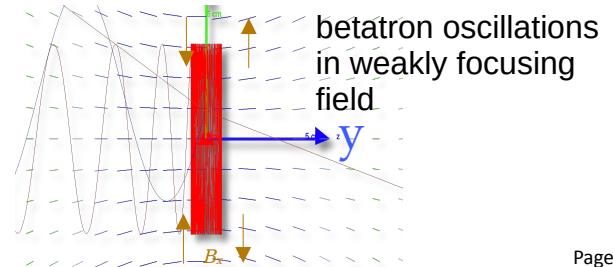
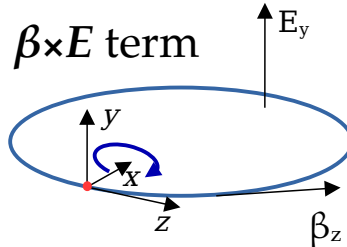
$$(\vec{\Omega}_{\text{MDM}})_z = -\frac{ea}{m_0} \left[\frac{p_{y0}}{p_z} \sin(\omega_\beta t) \left(\frac{\beta_z}{c} \left(1 - \frac{1}{a(\gamma^2 - 1)} \right) E_{ex} - \left(\frac{\gamma - 1}{\gamma} \right) B_y \right) + B_z \right]$$



oscillations due to the projection of the main solenoid field along the momentum



$$(\vec{\Omega}_{\text{MDM}})_x = -\frac{ea}{m_0} \left[\frac{\beta_z}{c} \left(1 - \frac{1}{a(\gamma^2 - 1)} + \frac{1}{\beta_z^2} \right) E_y + \Phi_0 \cos(\omega_\beta t + \phi_0) \rho y_0 + B_x \right]$$

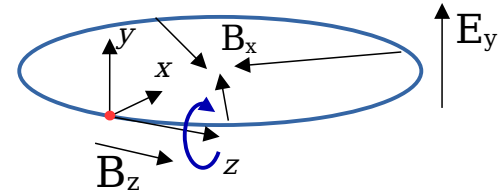


Average over all orbits

- If we take the average over all muon orbits the periodic oscillations disappear and we are left with three terms that could lead to a false EDM signal:

$$\langle \Omega_{\hat{z}} \rangle = -\frac{ea}{m_0} \langle B_z \rangle \quad \langle \Omega_{\hat{x}} \rangle = -\frac{ea}{m_0} \langle B_x \rangle$$

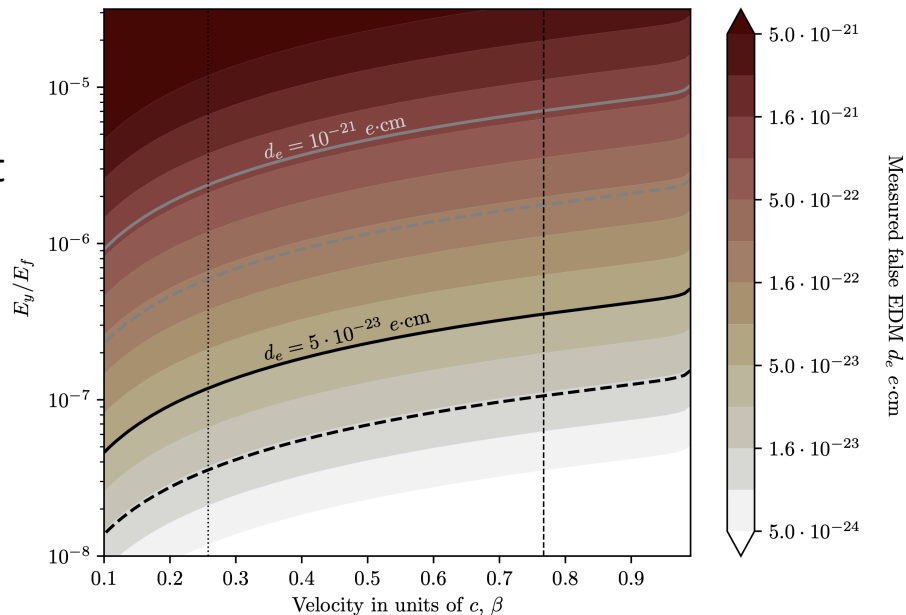
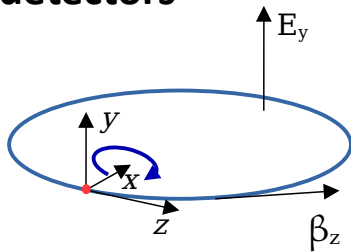
$$\langle \Omega_{\hat{z} \times \hat{y}} \rangle = -\frac{ea}{m_0 c} \left(\frac{1}{a(\gamma^2 - 1)} - 1 + \frac{1}{\beta_z^2} \right) \langle \beta_z E_y \rangle$$



- Net B -field component along the momentum $B_z \rightarrow$ non-zero if there is current flowing through the muon orbit
- Net radial B -field component $B_x \rightarrow$ can be non-zero due to residual fields from the magnetic kick
- Radial magnetic field in the reference frame of the muon due to a $\beta \times E$ term \rightarrow non-zero if there is E -field perpendicular to the muon orbit

Constraints on the average horizontal E-field

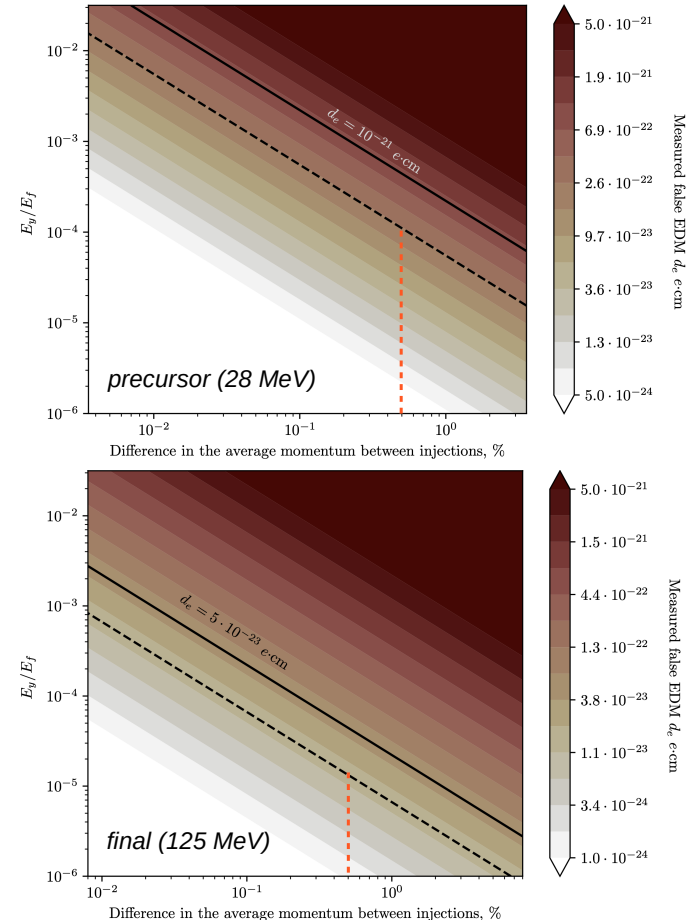
- Limit on the average E_y field as a function of the muon velocity shown as a fraction of the radial component
- The limit is 0.5 ppm for the precursor experiment and 0.1 ppm for the final experiment
- **This effect can be largely cancelled if particles are injected alternatively CW and CCW and subtracting counts in the detectors**



$$\langle \Omega_{\hat{z} \times \hat{y}} \rangle = -\frac{ea}{m_0 c} \left(\frac{1}{a(\gamma^2 - 1)} - 1 + \frac{1}{\beta_z^2} \right) \langle \beta_z E_y \rangle$$

Average velocity for CW and CCW injection

- Using alternating injection directions the average muon velocities for CW and CCW rotations must be similar in order to cancel the systematic
- The figures show the allowed difference in average momentum between CW and CCW injections in order to cancel the effect of E_y
- Limits improve to ~ 200 ppm for precursor and ~ 30 ppm for final assuming 0.5% difference between CW and CCW momenta
- Note: E_y is assumed to be constant between injections



Sources of E_y field: electrode alignment

- The E field of an infinitely long coaxial cylinders is:

$$\vec{E}(\vec{r}) = \frac{V}{\log \frac{b}{a}} \begin{pmatrix} x/r^2 \\ y/r^2 \\ 0 \end{pmatrix}$$

Shifting the field by r_0 and rotating by α gives:

$$\vec{E}' = R_y(\alpha) \vec{E}(R_y^{-1}(\alpha) \vec{r} + \vec{r}_0) = V_0 \begin{pmatrix} \frac{\xi}{\rho^2} \cos \alpha \\ \frac{v}{\rho^2} \\ -\frac{\xi}{\rho^2} \sin \alpha \end{pmatrix}$$

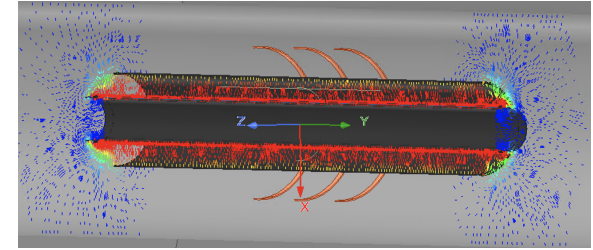
$$V_0 = \frac{V}{\log \frac{b}{a}}, \quad v = y + y_0, \quad \xi = x_0 + x \cos \alpha - z \sin \alpha \quad \text{and} \quad \rho^2 = \xi^2 + v^2$$

- Then average the new field out over a circular orbit:

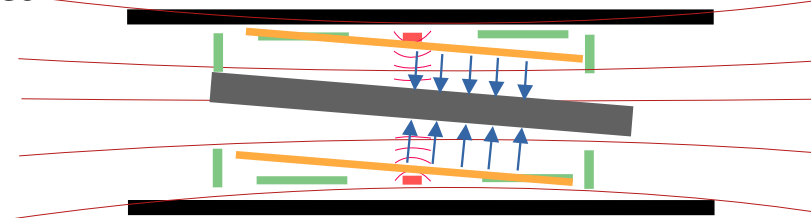
$$\langle E'(\rho, \zeta) \rangle = \frac{1}{2\pi} \int_0^{2\pi} E' d\phi$$

- It can be shown (numerically for now) that:

$$\langle E'(\rho, \zeta) \rangle = \langle E(\rho, \zeta) \rangle$$



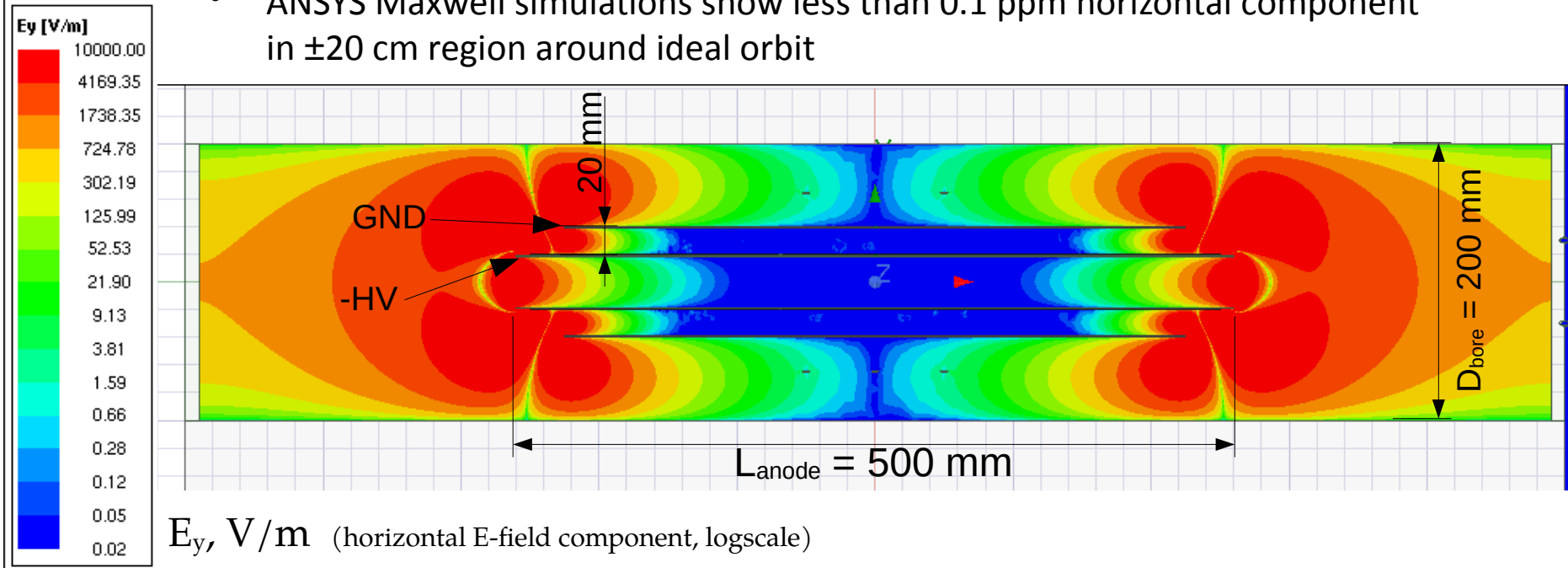
Misalignment of the electric field



- For a circular orbit the misalignment of the anode or cathode cannot introduce a net horizontal E-field (that was not there before)
- It also does not affect the 'frozen spin' condition

Sources of E_y field: fringe fields

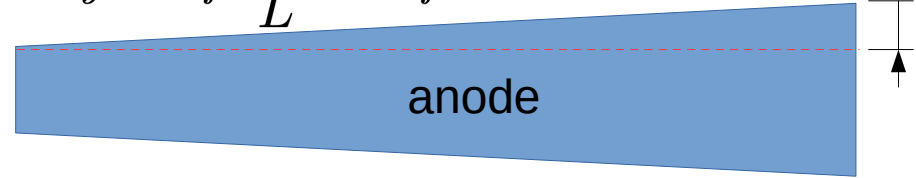
- The assumption for infinite coaxial cylinders holds if there are negligible fringe field in the region of interest
- ANSYS Maxwell simulations show less than 0.1 ppm horizontal component in ± 20 cm region around ideal orbit



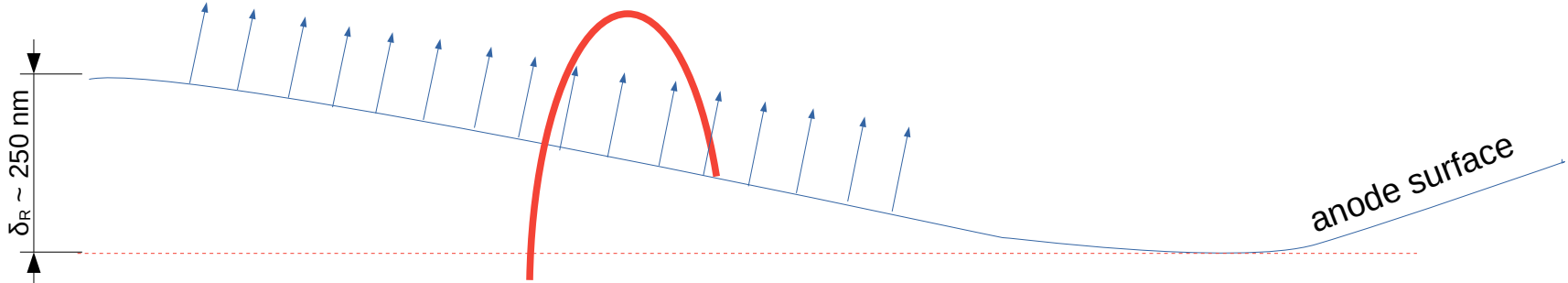
Sources of E_y field: electrode non-uniformity

- Tapered cone shaped electrodes

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



- Smoothness of the electrodes close to the muon orbit (few centimeters)



- Generally sub-micrometer surface smoothness is possible with common machining and polishing techniques
- Cylindricity in the order of 50 nm is measurable even on large samples

Limits on real spin precession effects

Parameter	Expected value	Effect	False EDM signal	Fraction of target EDM sensitivity ($5 \times 10^{-23} \text{ e} \cdot \text{cm}$)
Tapered cone shape electrodes*	Anode: $\Delta_R < 2.5 \text{ } \mu\text{m}$ Cathode: $\Delta_R < 2.5 \text{ } \mu\text{m}$	10 ppm horizontal E-field component CW-CCW injection 0.5% difference in average momenta	2×10^{-23}	40%
Electrode local (cone shaped) smoothness* ($\pm 2 \text{ cm}$ around ideal orbit)	Anode: $\delta_R < 0.25 \text{ } \mu\text{m}$ Cathode: $\delta_R < 0.25 \text{ } \mu\text{m}$	25 ppm horizontal E-field component CW-CCW injection 0.5% difference in average momenta	4×10^{-23}	80%
Decay time of radial B field from magnetic kicker	$< 50 \text{ ns}$	Residual radial B-field (spin precession around radial direction)	5×10^{-24}	10%
Net current flowing through area enclosed by muon orbit	$< 10 \text{ mA}$	Azimuthal B-field (spin precession around momentum)	3×10^{-24}	6%

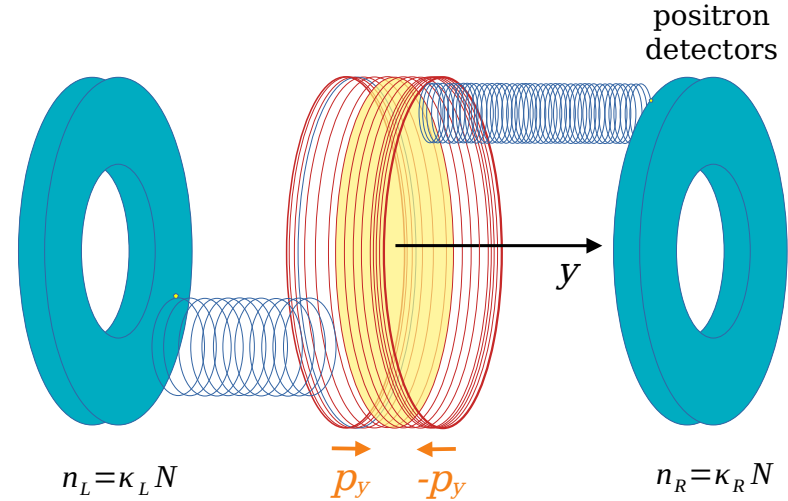
*assuming electrode shape does not depend on magnetic field orientation

A solid grey square is positioned to the left of the title text.

Systematic effects related to apparent spin precession

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

- Let us assume that there is some effect that changes the total detection efficiency of both detectors and it is exponential in nature

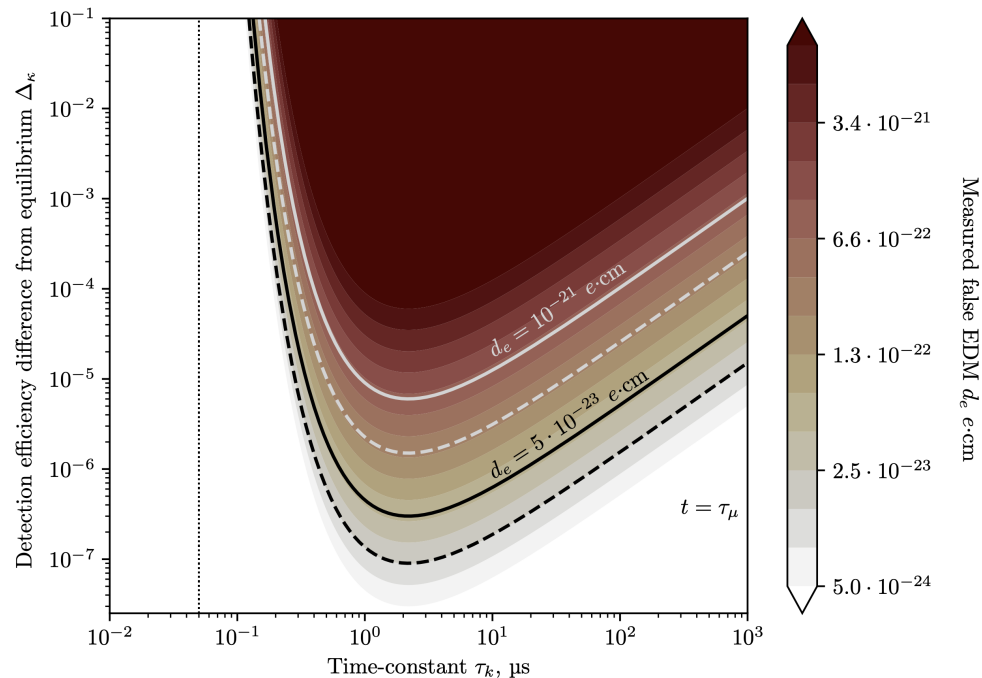
- Detection efficiency of up and downstream detectors:

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

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

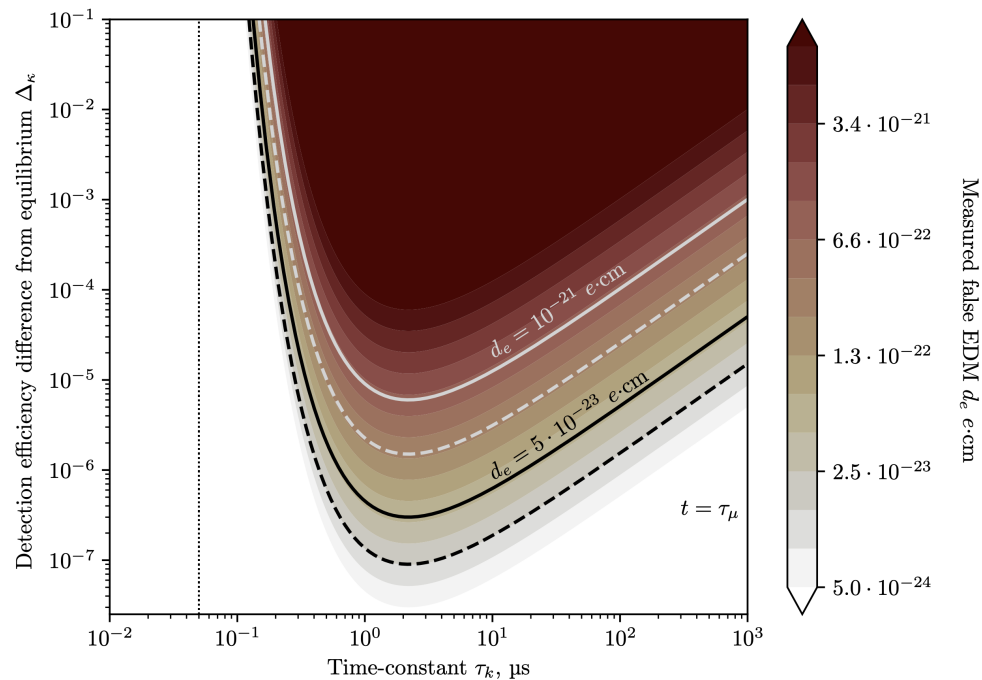
- Change in measured asymmetry with time:

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



Constraints on the total detection efficiency

- Note here that the total detection efficiency refers not only to the efficiency of scintillators/silicon detectors/etc but also includes the geometrical detection efficiency
 - e.g. kicker field pushes positrons preferentially in one direction
- **The effect would not be cancelled by alternating CW and CCW injection**



Measuring the apparent systematic effects

- If the electrical field is tuned to a value such as to enhance the $g-2$ precession the spin can make many rotations during the muon lifetime
- Any EDM or real spin precession systematic effects will be suppressed and the average spin precession will be zero
- Thus if any asymmetry is observed it will be due to the changing detection efficiency

Conclusions

- Constraints on the main systematic effects due to EM fields were calculated using an analytical description of the spin precession in the EM fields of the experimental setup
- Stringent limits on the horizontal component of the electric field were identified
 - The systematics due to the electric field would be largely cancelled by clockwise and counter-clockwise muon injection
 - Limits on the CW and CCW average muon momentum are shown
- Constraints on the radial and azimuthal B-fields were placed
- Limits on the early-to-late detection efficiency of the EDM detectors were calculated and a method for the study of the systematic is discussed

Thank you for the attention!

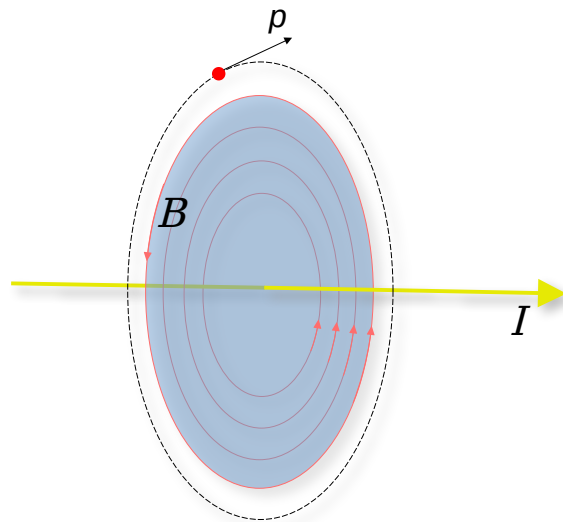
**muonEDM
collaboration kick-off
meeting May 2022
(Pisa, Italy) →**



Limit on the B -field parallel to the momentum

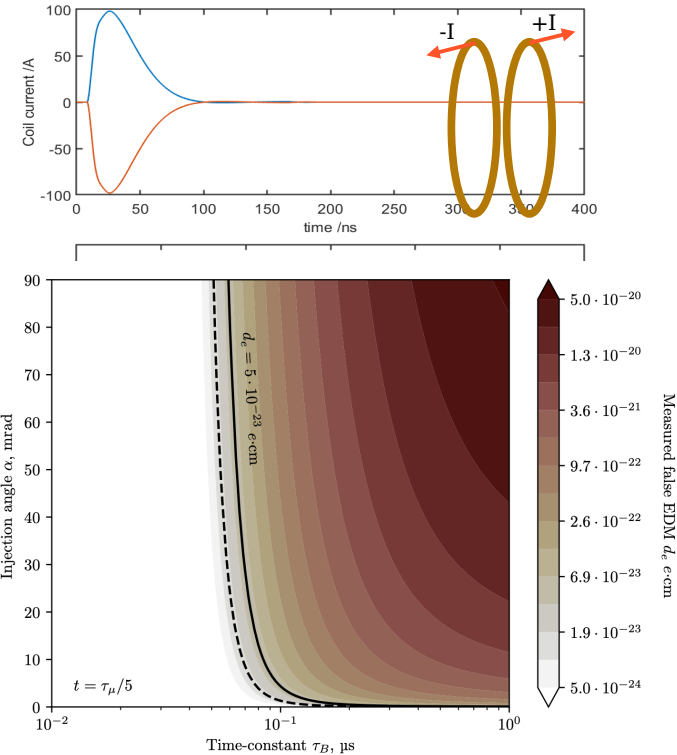
- Non-zero average B_z field if there is electric current flowing through the area enclosed by the muon orbit
- Write net current!
- From Biot-Savart's law we can give a limit on the systematics due to such current
- Assuming non-insulated wire at the center of the orbit:
 - Precursor: $I < 250$ mA
 - Final experiment: $I < 40$ mA

$$\langle \Theta_{\hat{z}} \rangle = -\frac{ea}{m_0} \langle B_z \rangle t.$$



Limit on the radial B -field

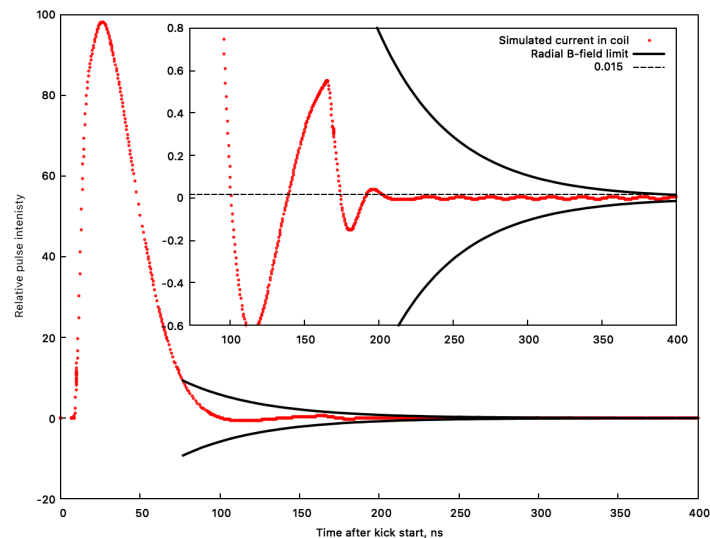
- Limit on the kicker field decay time with relation to the injection angle
- Assumptions:
 - half-sine kicker field intensity
 - end of the kick is considered to be at the 10% from maximum level
 - exponential decay of the ringing signal with time constant τ_B
 - the limit is such that the influence of the residual field is less than a given d_e at ~ 400 ns time



Note: the constraint is lower for later times and stronger for earlier times

Limit on the radial B -field

- Simulated short current pulse for the two anti-Helmholtz coils
- The solid black line shows the limiting decay time for an exponentially decaying pulse that goes below the limit at 400 ns (overshoot or undershoot)
- The influence of the simulated kicker field to the observed spin precession is negligible after 200 ns



Surface smoothness

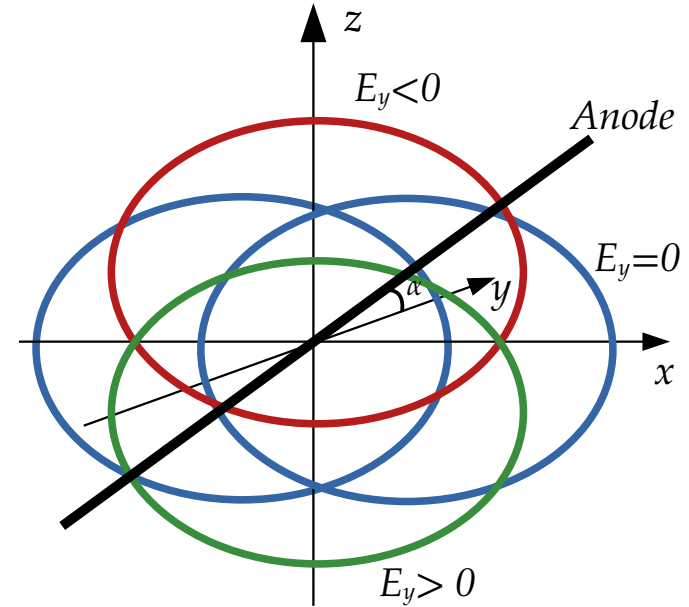
- Surface smoothness at the submicron level seems achievable by a lot of methods

<https://www.a-i-t.com/cnc-machining-services/surface-finish-comparison-chart>

New ISO scale numbers		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
RMS Microinches (μ'')	0.5	1.1	2.2	4.4	8.8	17.6	35.2	64.3	137.5	275	550	1100	2200
RMS Micrometers (μm)	0.013	0.027	0.055	0.11	0.22	.44	.88	1.6	3.44	6.88	13.75	27.5	55
CLA or R_a microinch (μ'')	0.5	1	2	4	8	16	32	63	125	250	500	1000	2000
R_a micrometer (μm)	0.012	0.03	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	12.5	25	50
Sand Casting													
Hot Rolling													
Forging													
Permanent-Mold Casting													
Investment Casting													
Extruding													
Cold Rolling													
Diecasting													
Flame Cutting													
Sawing													
Planing													
Drilling													
EDM													
Milling													
Laser Cutting													
Reaming													
Broaching													
Turning and Boring													
Tumbling													
Roller Burnishing													
Grinding													
Honing													
Electro-Polishing													
Polishing													
Lapping													
Superfinishing													

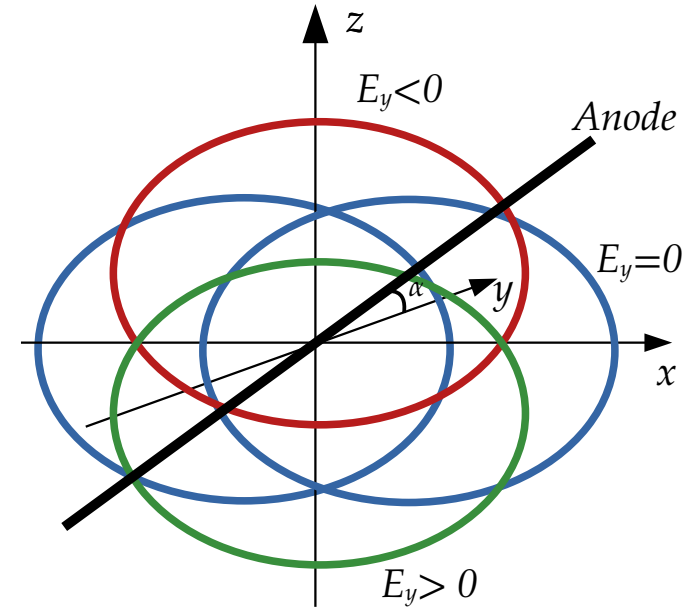
Non-circular muon orbit

- A non-zero average E_y field can be generated if the orbit of the muons is elliptical and at the same time it is not perpendicular to the axis of the anode.
 - the average field will be zero if the center of the orbit lies on the x axis
 - it is positive if it lies on the z axis above zero and negative if below zero
- In the general case the orbit will be eccentric due to the inward radial Lorentz force from the freeze field



Non-circular muon orbit

- The effect was observed also in the Geant4 simulations and is consistent with the analytical estimate
- Calculations with the analytical equations show that for $\alpha = 0.1^\circ$ and orbit displacements up to 5 mm the eccentricity of the orbit should be kept below 0.1
- The eccentricity caused by the freeze field is significantly lower and does not pose a problem
- This effect could constrain the magnetic field uniformity (analysis pending)



Finally...

- The equations describe a relatively general case with a weakly focusing field and imperfect «freeze field». The muon starts at position (ρ, y_0) and spin with direction (ϕ_0, Θ_0) and there is non-zero E_y field.

Initial spin direction:

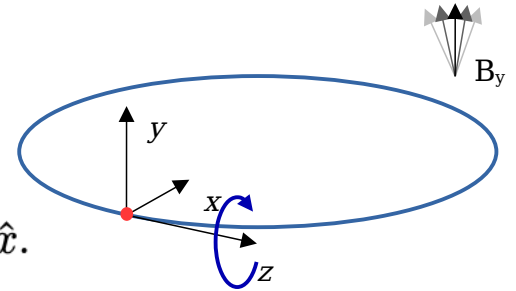
$$\phi_0 = \arctan\left(\frac{S_x}{S_z}\right),$$

$$\Theta_0 = \arctan\left(\frac{\sqrt{S_x^2 + S_z^2}}{S_y}\right) - \frac{\pi}{2}$$

$$\Theta_{\hat{z}}(t) = \frac{e}{m_0} \left[\frac{p_{y0}}{p_z} \frac{1}{\omega_\beta} \cos(\omega_\beta t) \left(\frac{\beta_z}{c} \left(a - \frac{1}{\gamma^2 - 1} \right) E_{ex} - a \left(\frac{\gamma - 1}{\gamma} \right) B_y \right) + \frac{1}{\omega_y} a B_z \right] \sin(\omega_y t + \phi_0) \hat{z}.$$

$$\Theta_{\hat{x}}(t) = -\frac{ea}{m_0} \left[\frac{1}{\omega_\beta} \Phi_0 \sin(\omega_\beta t + \phi_0) \rho y_0 \right] \cos(\omega_y t + \phi_0) \hat{x}.$$

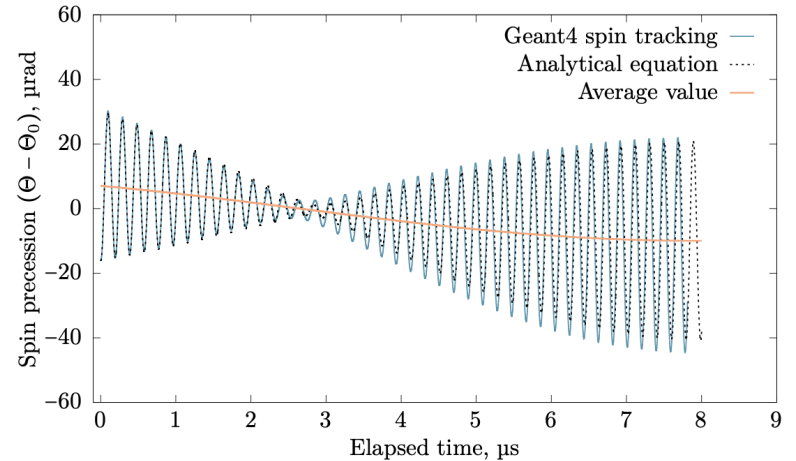
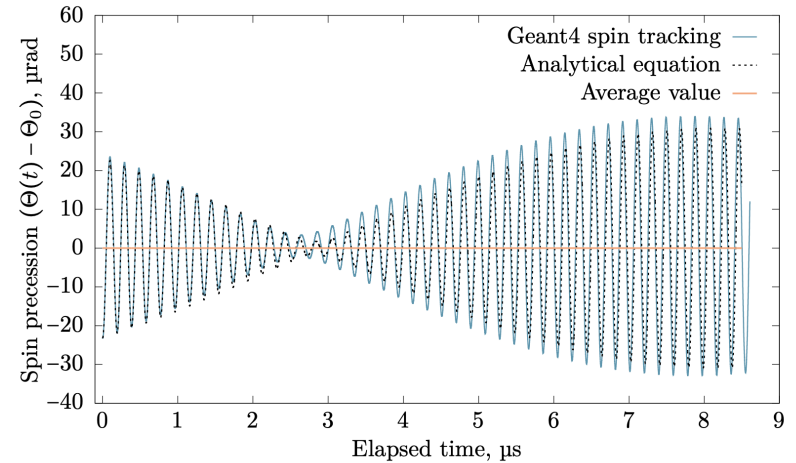
$$\Theta_v(t) = -\frac{ea}{m_0} \left[\left(\frac{1}{a(\gamma^2 - 1)} - 1 + \frac{1}{\beta_z^2} \right) \frac{\beta_z}{c} E_y + B_x \right] \frac{1}{\omega_y} \sin(\omega_y t + \phi_0) \hat{x}.$$



- The total is the sum of all contributions: $\Theta = \Theta_{\hat{x}} + \Theta_{\hat{z}} + \Theta_v + \Theta_0.$

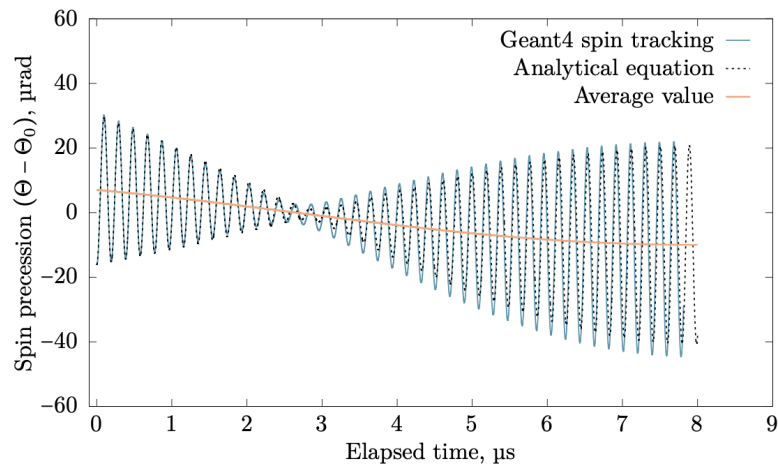
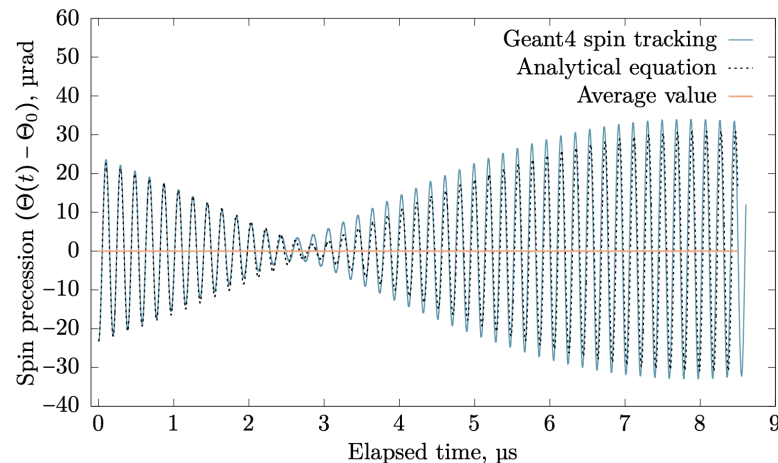
Comparison with G4

- Compared the analytical equations with a Geant4 simulation with the same parameters (weakly focusing coil current, radius; initial spin vector; etc...)
- In both attempts the frozen spin condition is not perfectly met (for illustration)
- Top: $E_y = 0$; Bottom: $E_y = E_{freeze}/10^6$
 - Note: bottom trend is similar to EDM of 10^{-21} e.cm



Comparison with G4

- Note that the oscillation frequency is not perfect as the fields are described by first order approximation
- Nevertheless, the equations describe the spin precession well in a very general scenario



Constraints on the injection angle

- Assuming a 100 ns wide half-sine pulse the figure shows the time between injection and start of the magnetic kick
- The fraction of lost muons is shown on the right y axis
- Perhaps injection angles between 1 and 5 degrees would be favourable

