Kicker eddy currents in the Fermilab Muon $g-2$ experiment

Maria Domenica Galati

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- How do we measure a_μ?
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What is the muon anomaly?

g-factor

$$\boldsymbol{\mu} = g\frac{q}{2m}\mathbf{s},$$

- Dirac equation $\Rightarrow g = 2 \Rightarrow \boldsymbol{\mu} = \frac{q}{m}\mathbf{s}$
- Coupling with virtual particles $\Rightarrow g \gtrsim 2 \Rightarrow \boldsymbol{\mu} = (1+a)\frac{q}{m}\mathbf{s}$

Magnetic anomaly

$$a = \frac{g-2}{2}$$

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Magnetic anomaly

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Why are we interested in a_μ?

It can be calculated very precisely...

$$a_\mu^{\mathrm{SM}}(\text{Nov. 2020}) = 116591810(43) \times 10^{-11} \quad (370 \text{ ppb})$$

...and also measured experimentally with a similar precision

$$a_\mu^{\mathrm{Exp.}}(\text{BNL 2006}) = 116592080(63) \times 10^{-11} \quad (540 \text{ ppb})$$

→ Accurately verify the theory

→ Search for NP contributions:

$$a_\mu^{NP} \approx C\left(\frac{m_\mu}{M_{NP}}\right)^2$$

The Muon $g-2$ Experiment at Fermilab

Principle of the experiment

Cyclotron frequency: $\omega_c = \frac{q}{m} B$

Spin precession frequency: $\omega_s = g \frac{q}{2m} B$

$$\Rightarrow \omega_a = \omega_s - \omega_c = a_\mu \frac{q}{m} B$$

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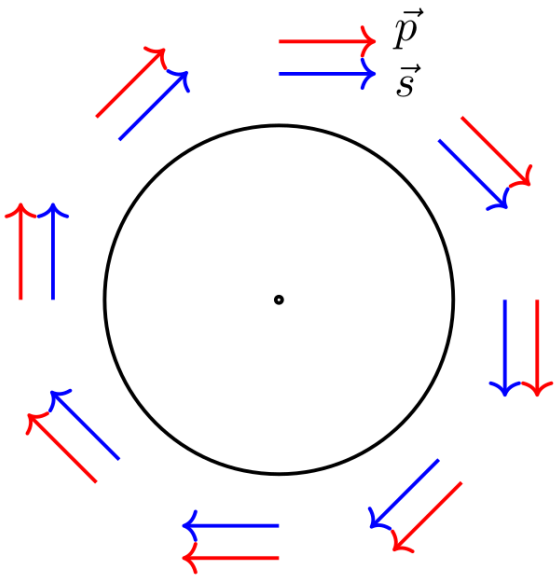
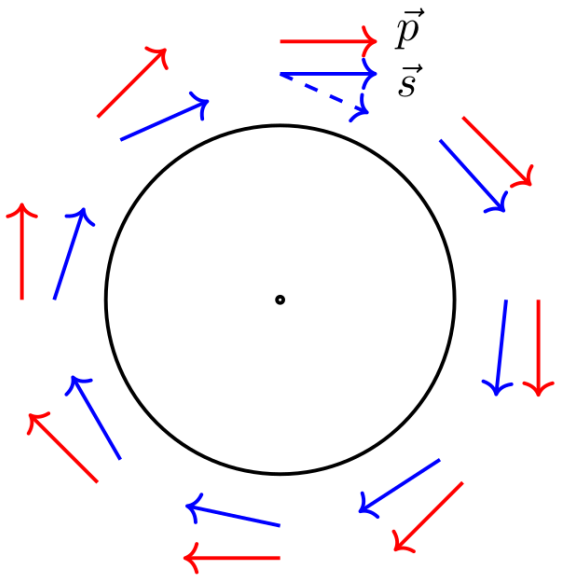
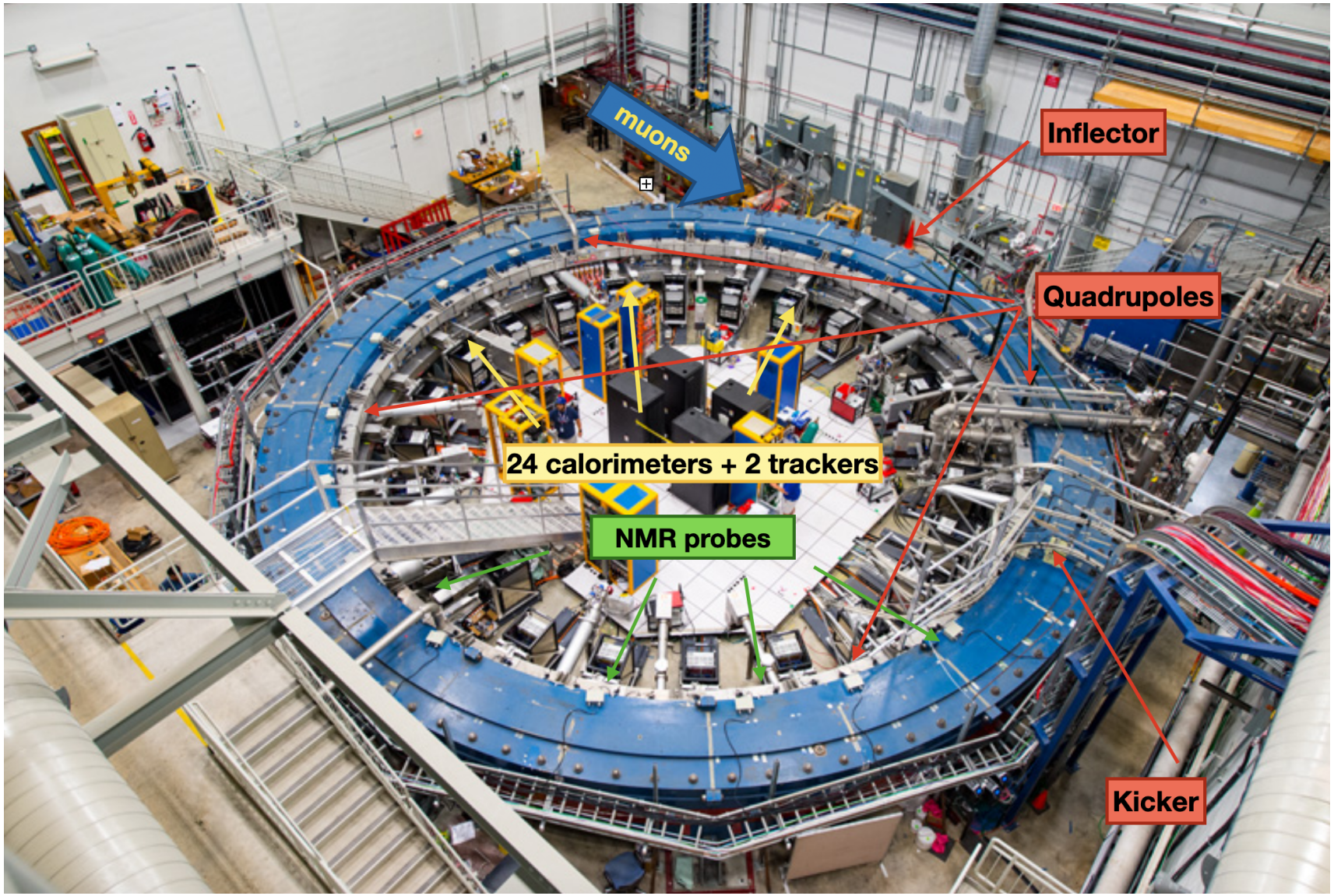


$g = 2$



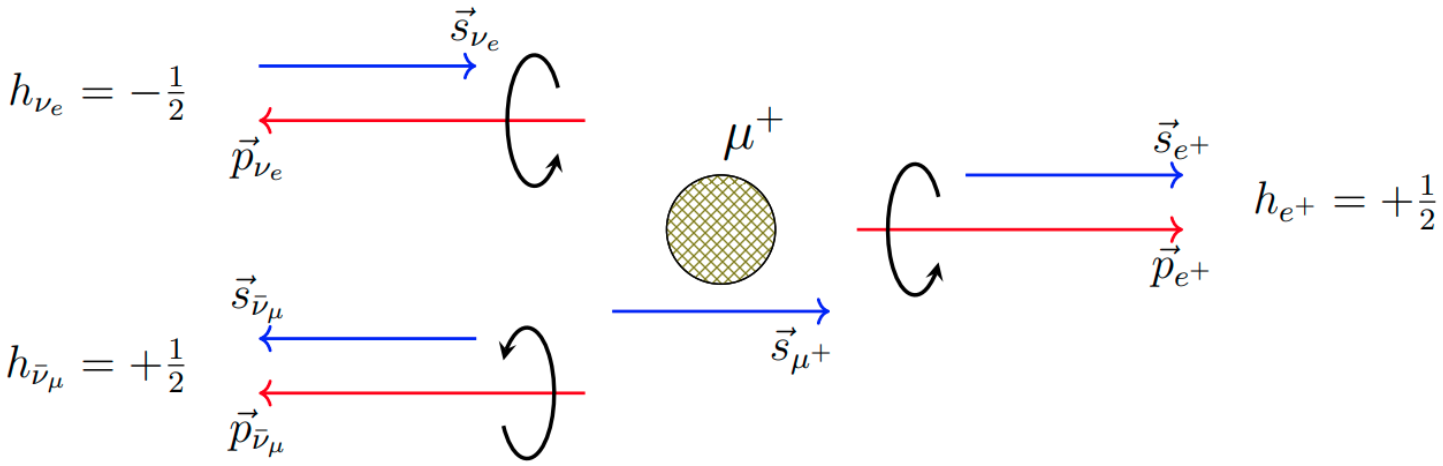
$g > 2$

The experiment



How do we measure the spin direction of the muons?

The most energetic positrons are emitted in the same direction of the muon's spin:



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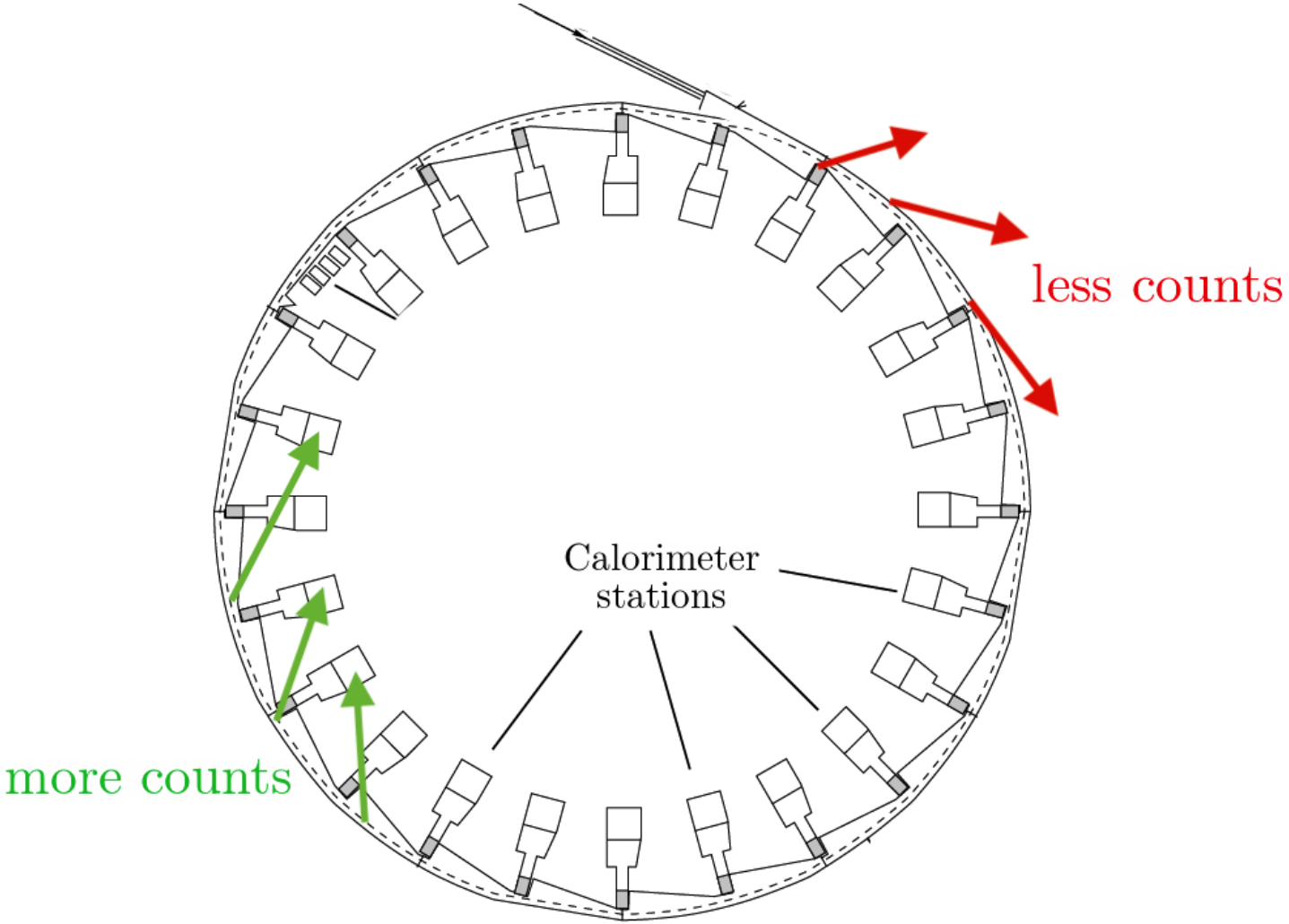
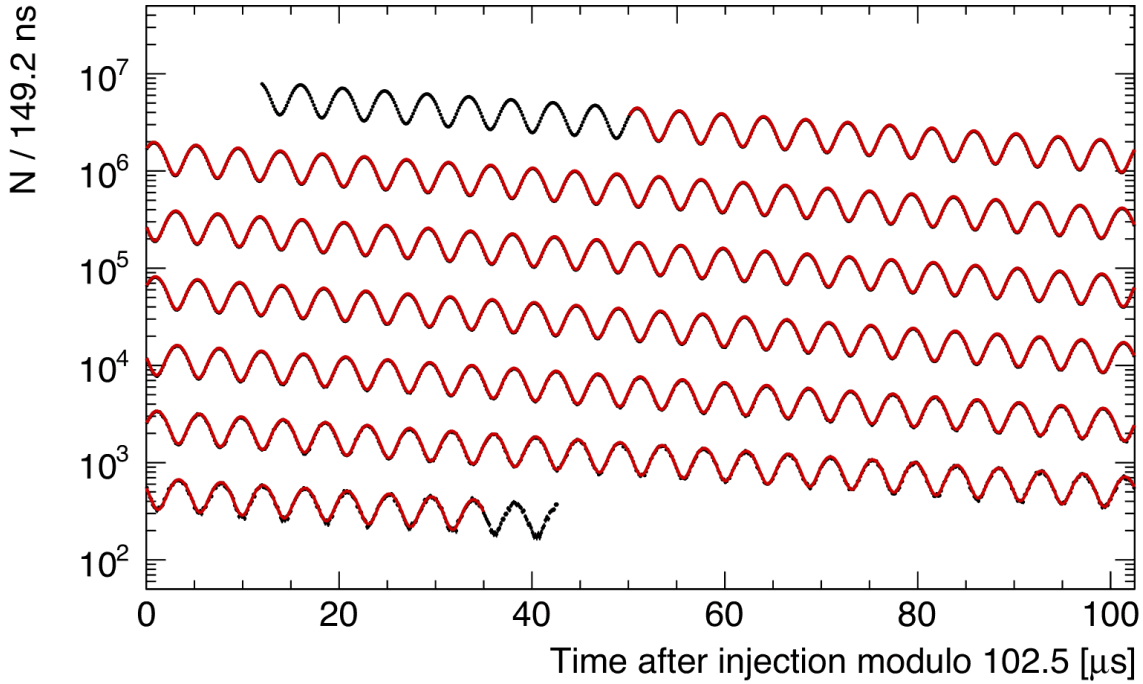


Measuring the anomalous precession frequency ω_a:

The number of positrons detected above a certain energy threshold oscillates with frequency ω_a:

5-parameter formula

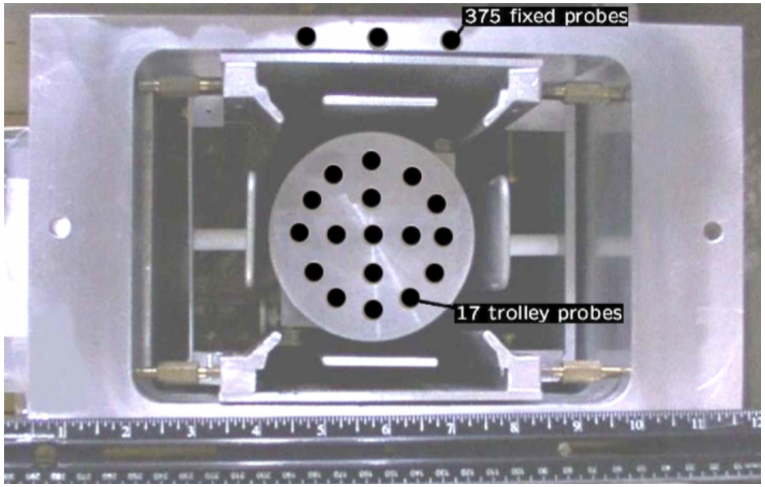
$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$



Computing a_μ

$$a_\mu = \frac{\omega_a}{B}\frac{m_\mu}{q}$$

B: measured using pulsed-proton NMR probes, and given by the measurement of the proton precession frequency $\tilde{\omega}_p$.



What the Muon $g-2$ Experiment actually measures is:

$$\mathcal{R}_\mu = \frac{\omega_a}{\tilde{\omega}_p}$$

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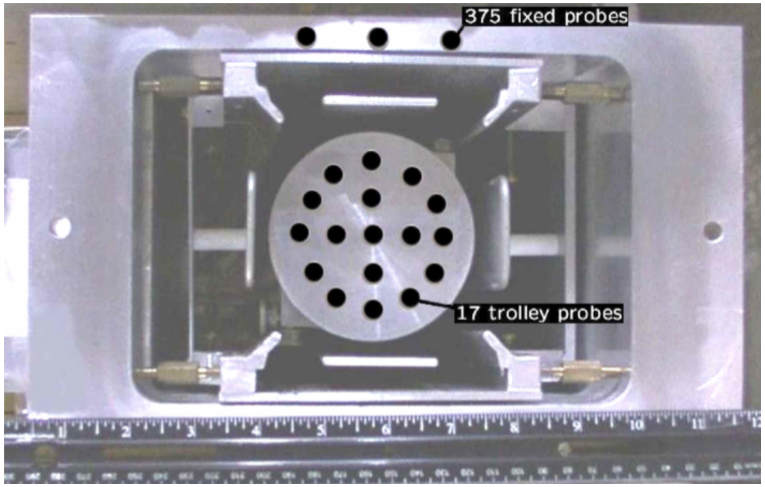

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$$\mathcal{R}_\mu = \frac{\omega_a}{\tilde{\omega}_p}$$

Corrections to $\mathcal{R}_\mu = \omega_a/\tilde{\omega}_p$

$$\mathcal{R}_\mu = \frac{\omega_a(1 + C_{ML} + C_E + C_P + C_{PA})}{\tilde{\omega}_p(1 + b_{EC} + b_Q)} \begin{array}{l} \rightarrow \text{beam dynamics} \\ \rightarrow \text{transient fields} \end{array}$$

- C_{ML}: muons lost from the storage region
- C_E: electric field correction
- C_P: some muons have a component of their velocity parallel to the magnetic field
- C_{PA}: acceptance effects

- b_{EC}: kickers transient field
- b_Q: quadrupoles transient field

Corrections to $\mathcal{R}_\mu$ (Run 1)

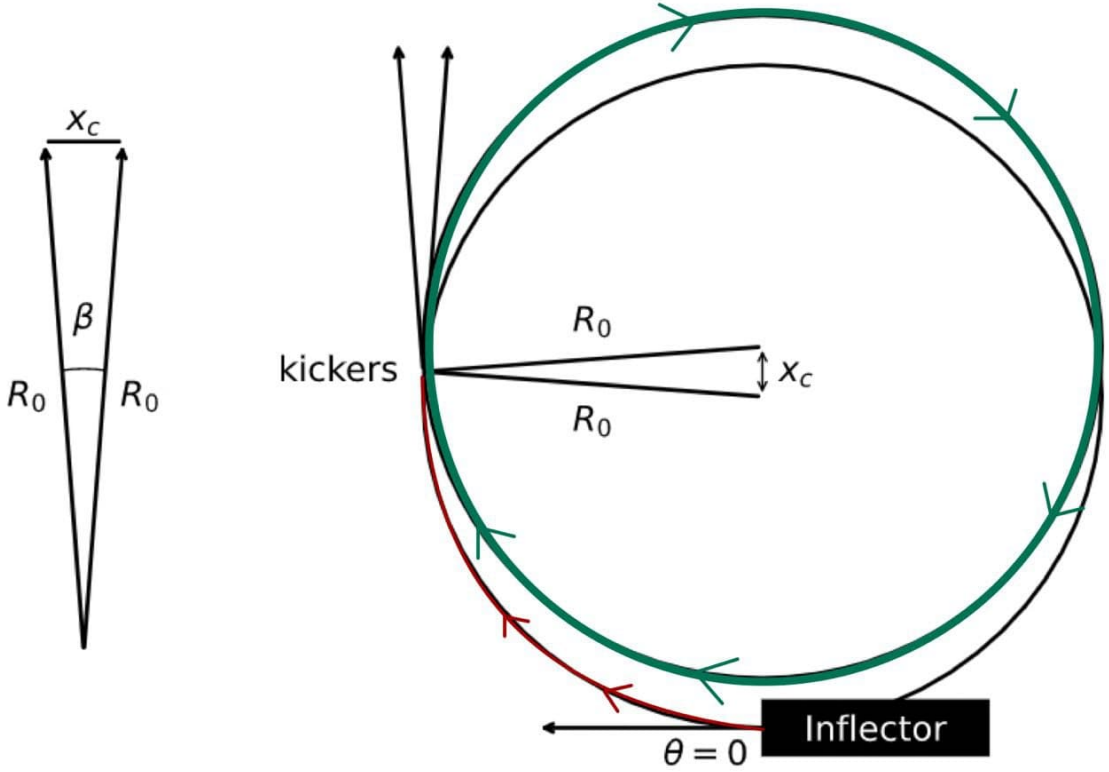
$$\mathcal{R}_\mu = \frac{\omega_a(1 + C_{ML} + C_E + C_P + C_{PA})}{\tilde{\omega}_p(1 + b_{EC} + b_Q)} \begin{array}{l} \rightarrow \text{beam dynamics} \\ \rightarrow \text{transient fields} \end{array}$$

Quantity	**Correction** [ppb]	**Uncertainty** [ppb]
ω_a (statistical)	-	434
ω_a (systematic)	-	56
C_{ML}	-11	5
C_E	489	53
C_P	180	13
C_{PA}	-158	75
$\tilde{\omega}_p$	-	56
b_{EC}	-27	37
b_Q	-17	92
$\mu_p(34.7\,°\mathrm{C})/\mu_e$	-	10
μ_μ/μ_e	-	22
$g_e/2$	-	0
Total systematic	-	157
Total fundamental factors	-	25
Totals	544	462

b_{EC}: Kicker Eddy Currents

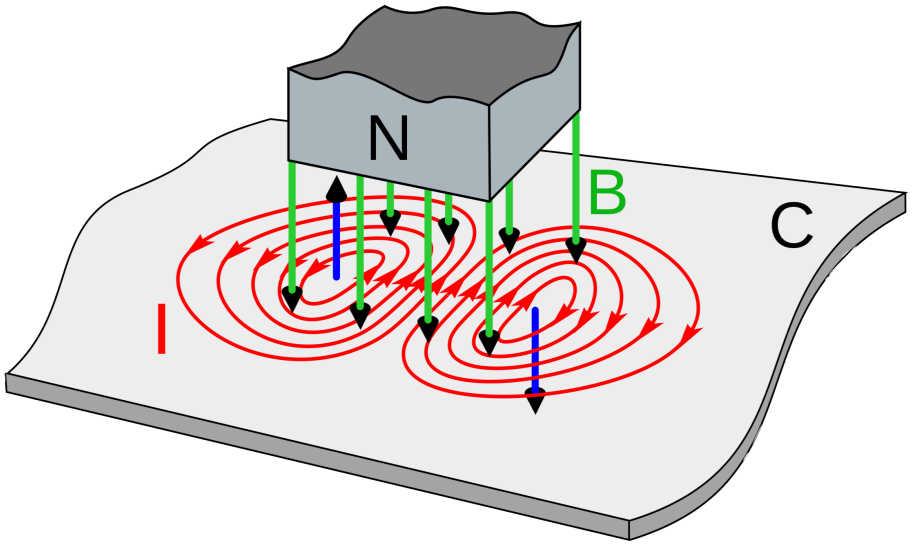
Kicker

Three kicker magnets steer the muon beam onto the ideal orbit.



High tension 137 kV in $\sim$ 120 ns: Faraday's law $\Rightarrow$ eddy currents

Eddy currents



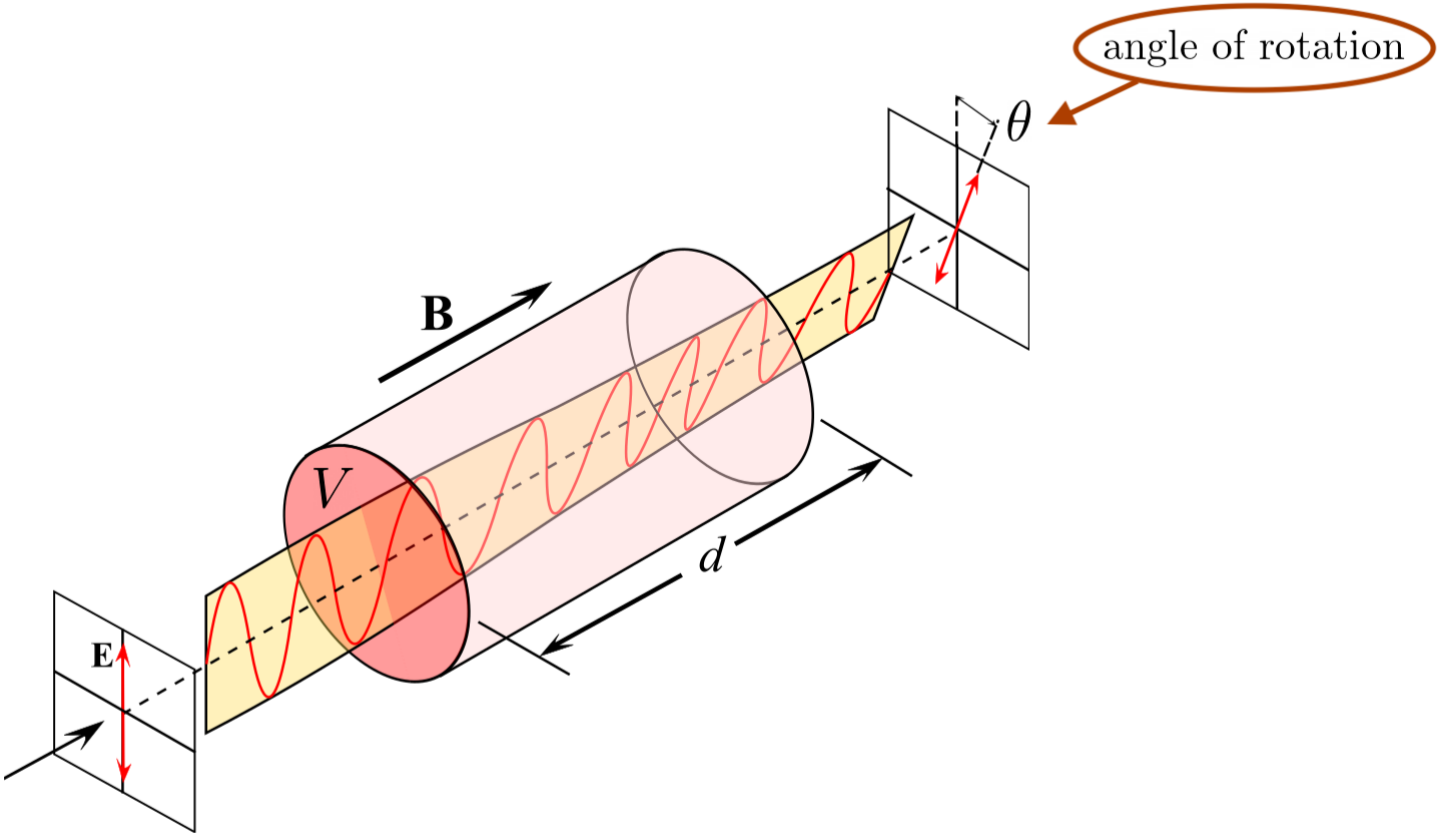
Problems

- Eddy currents $\Rightarrow$ transient magnetic field B_{EC}
- $\langle B_{EC} \rangle < 10^{-6} B_0$, $\tau_{EC} \sim 70\,\mu\text{s} \Rightarrow$ can't be measured with NMR probes

Faraday effect

The plane of polarization rotates by an angle that is proportional to the magnetic field:

$$\theta = VBd$$



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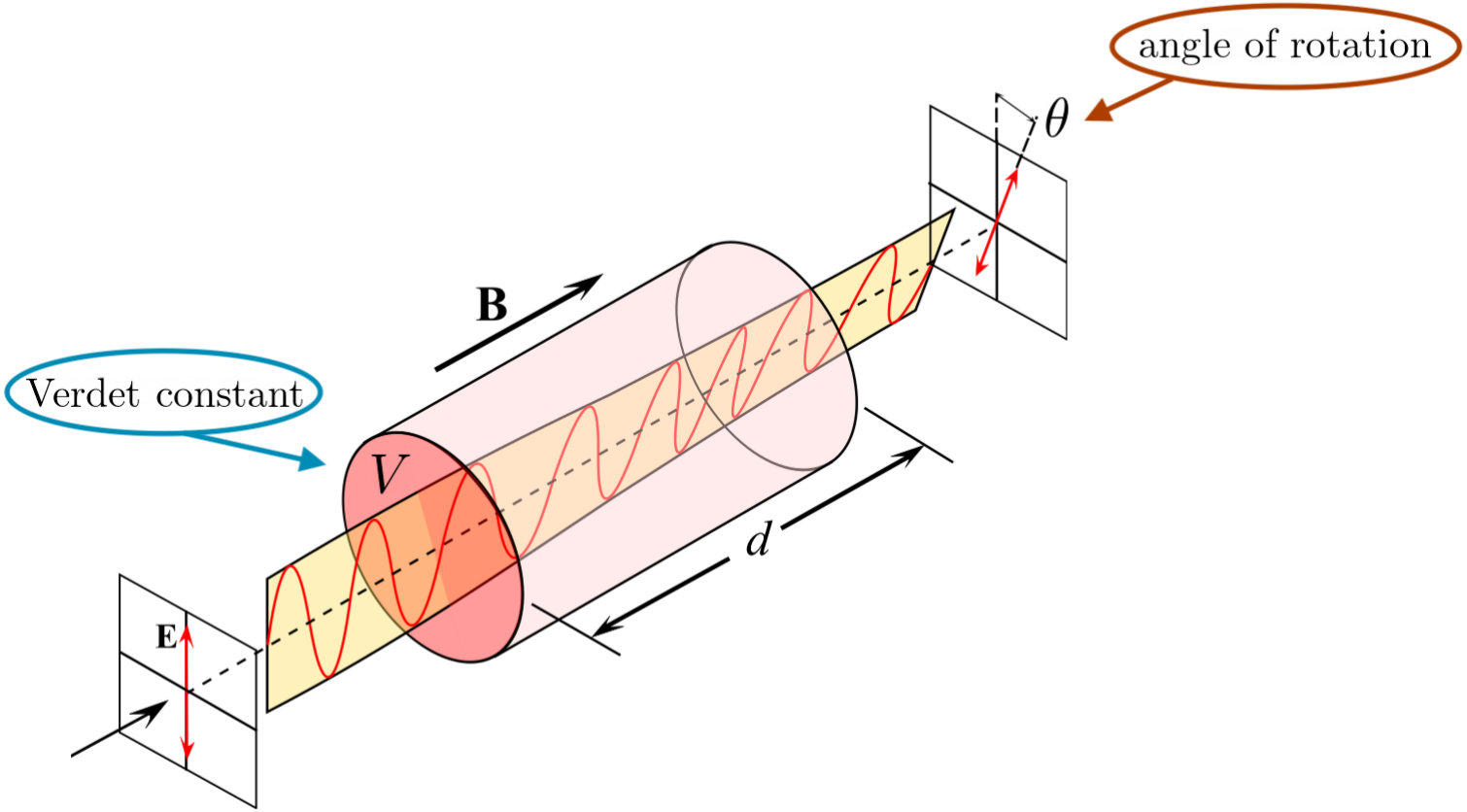

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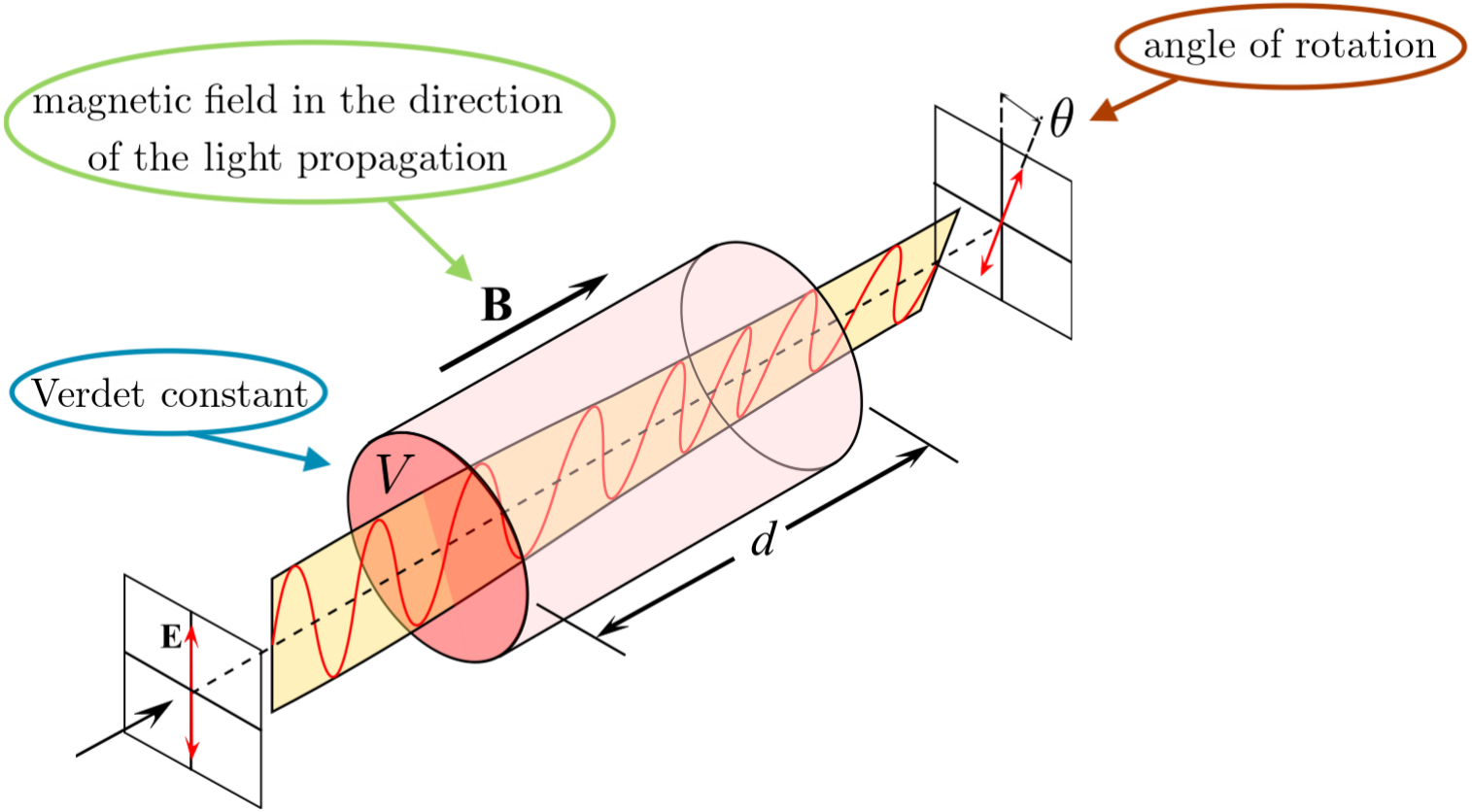

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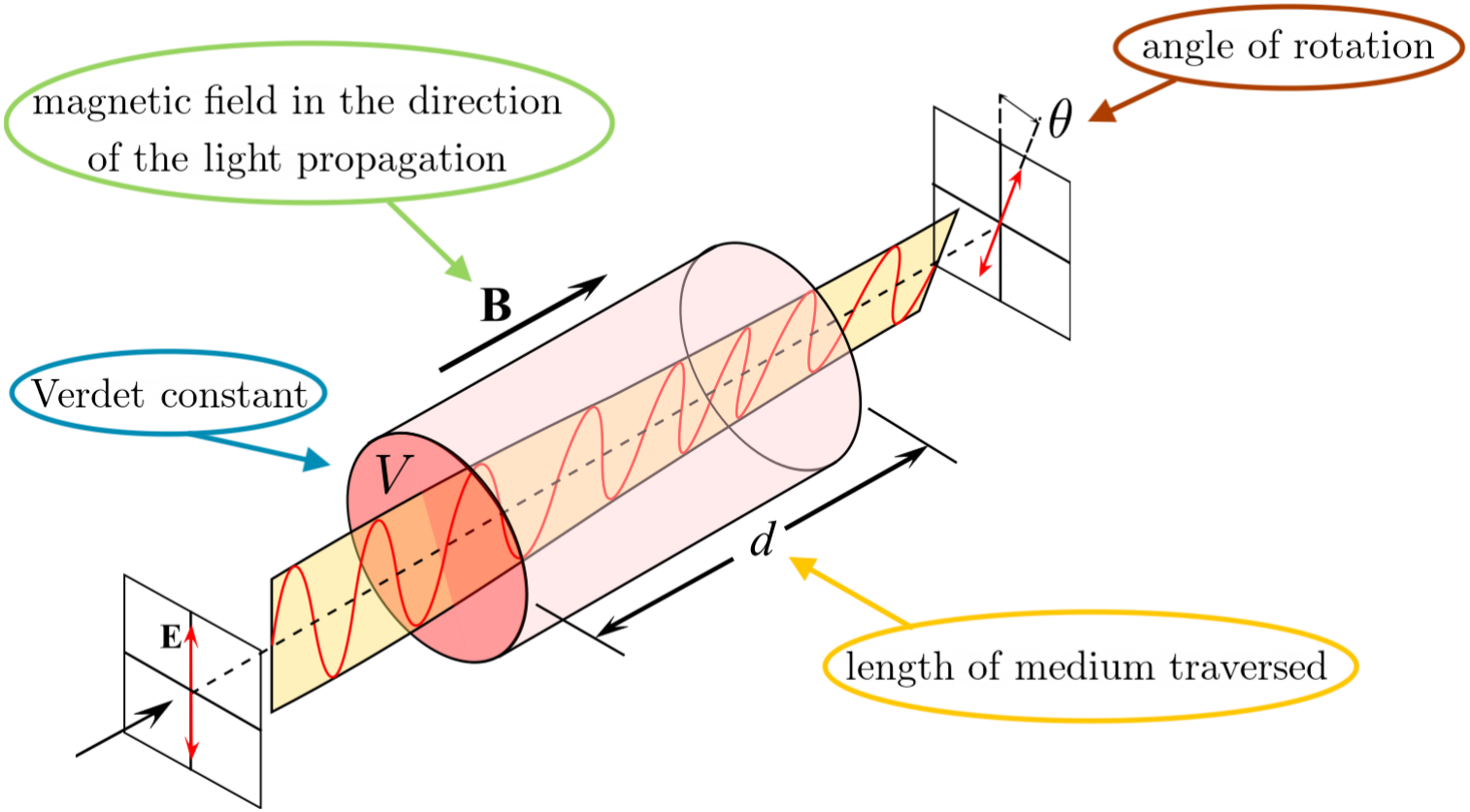

Ingredients to build a magnetometer based on the Faraday effect

- a polarized laser
- a high Verdet constant material: $Tb_3Ga_5O_{12}$ crystal
- something that allows to measure the rotation of the polarization

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- a polarized laser
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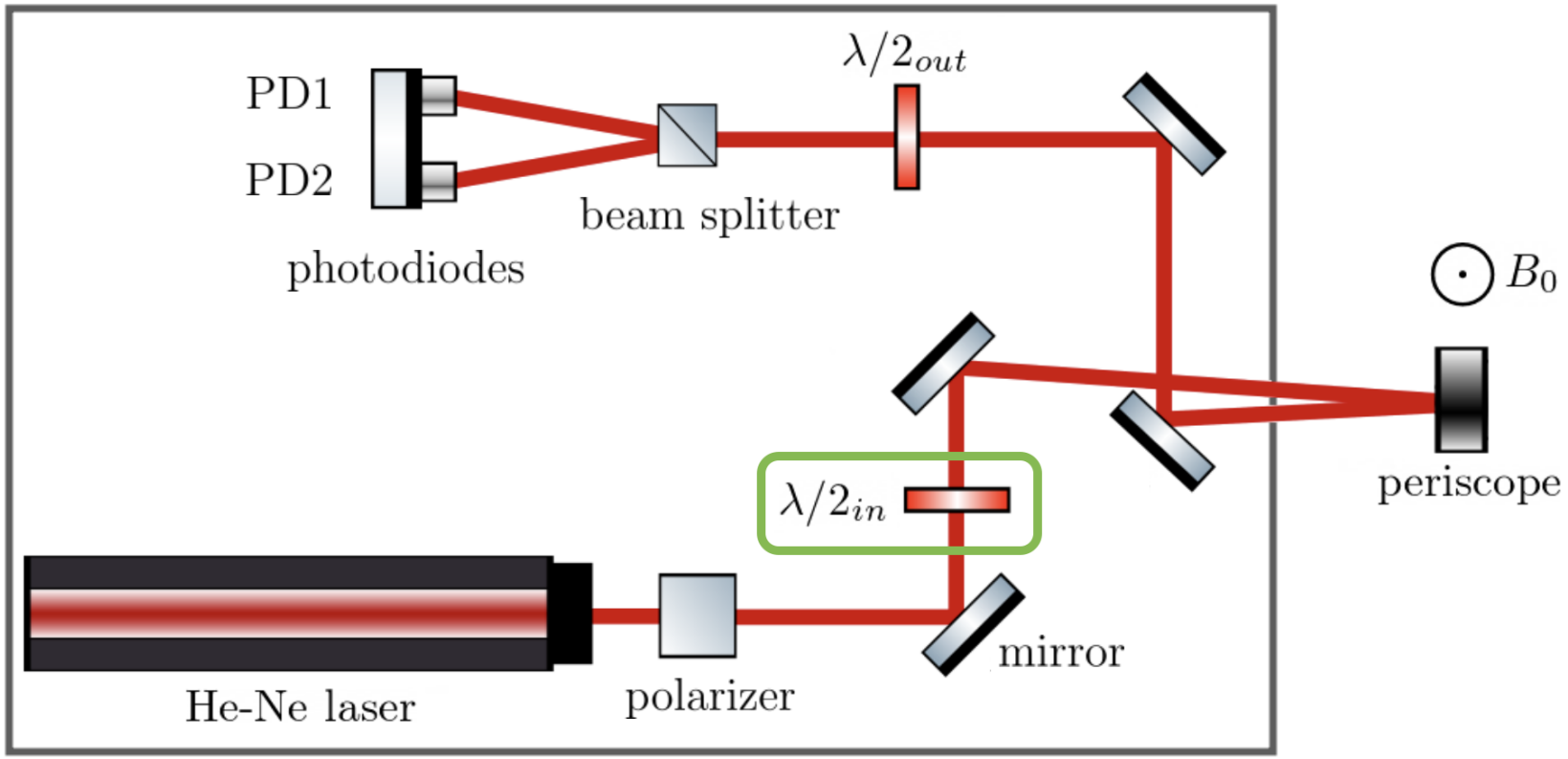
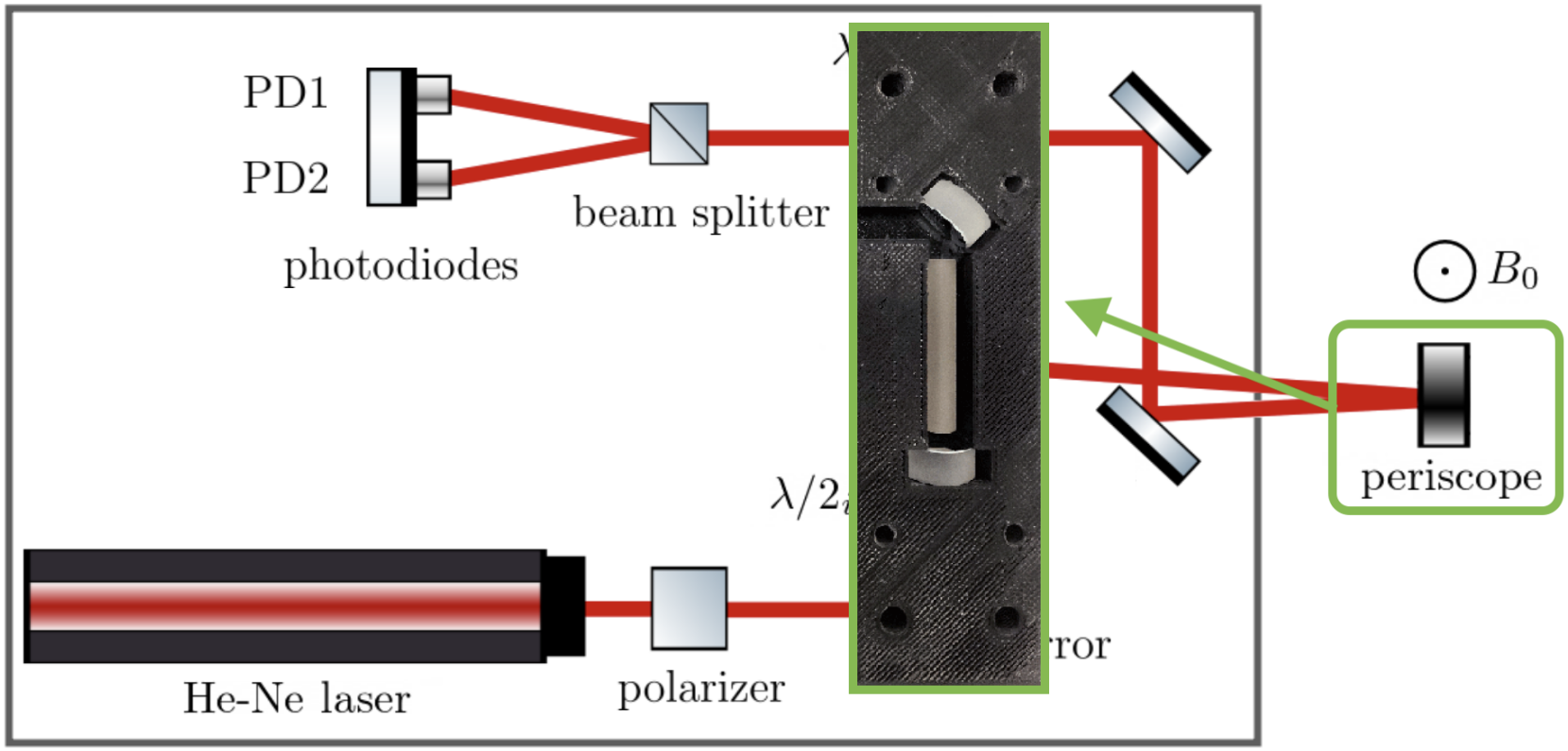
- something that allows to measure the rotation of the polarization
- a desperate Master student

Setup scheme



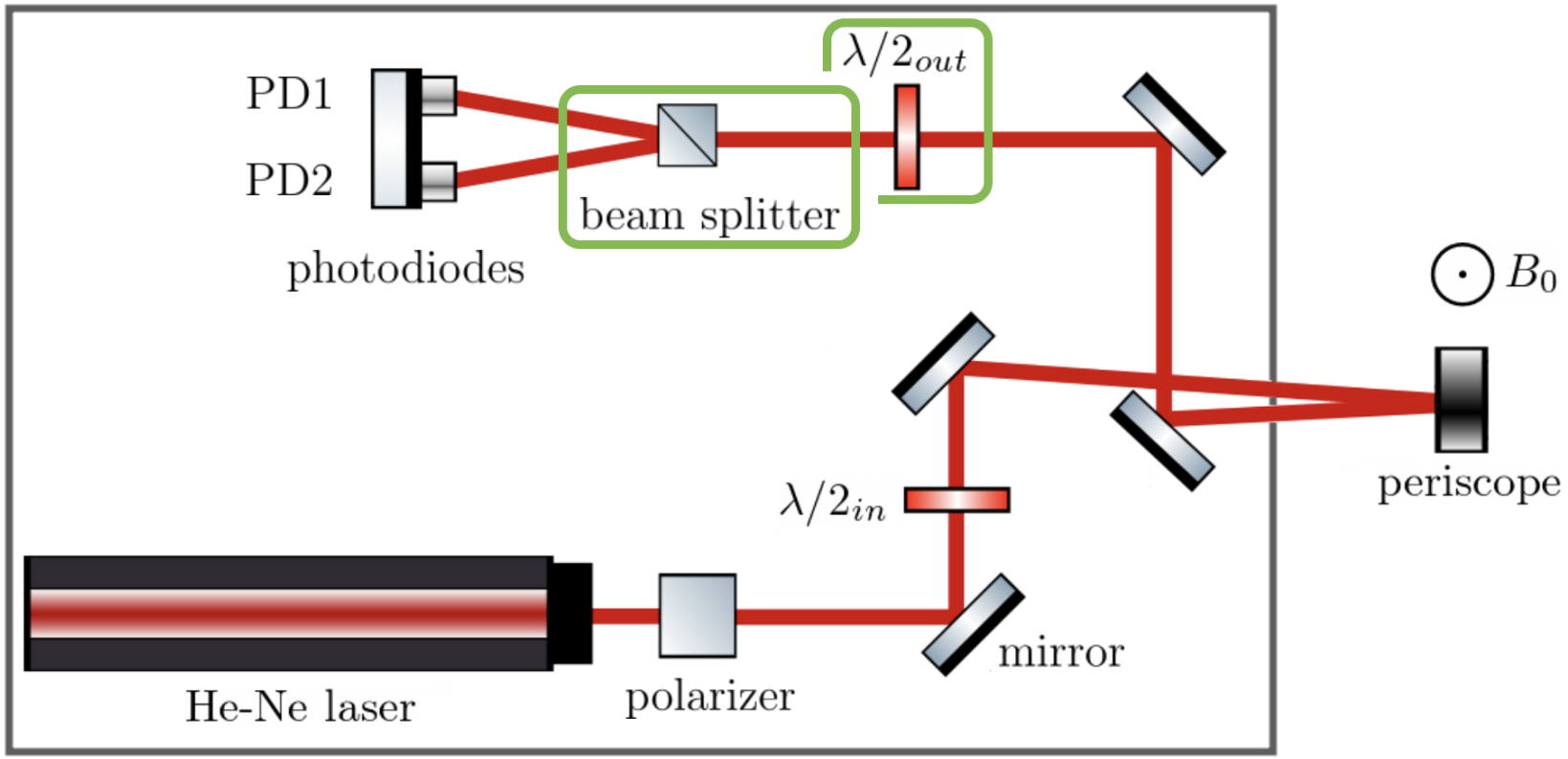
- Linearly polarized laser
- $\lambda/2_{in}$: optical device that rotates the polarization state

Setup scheme



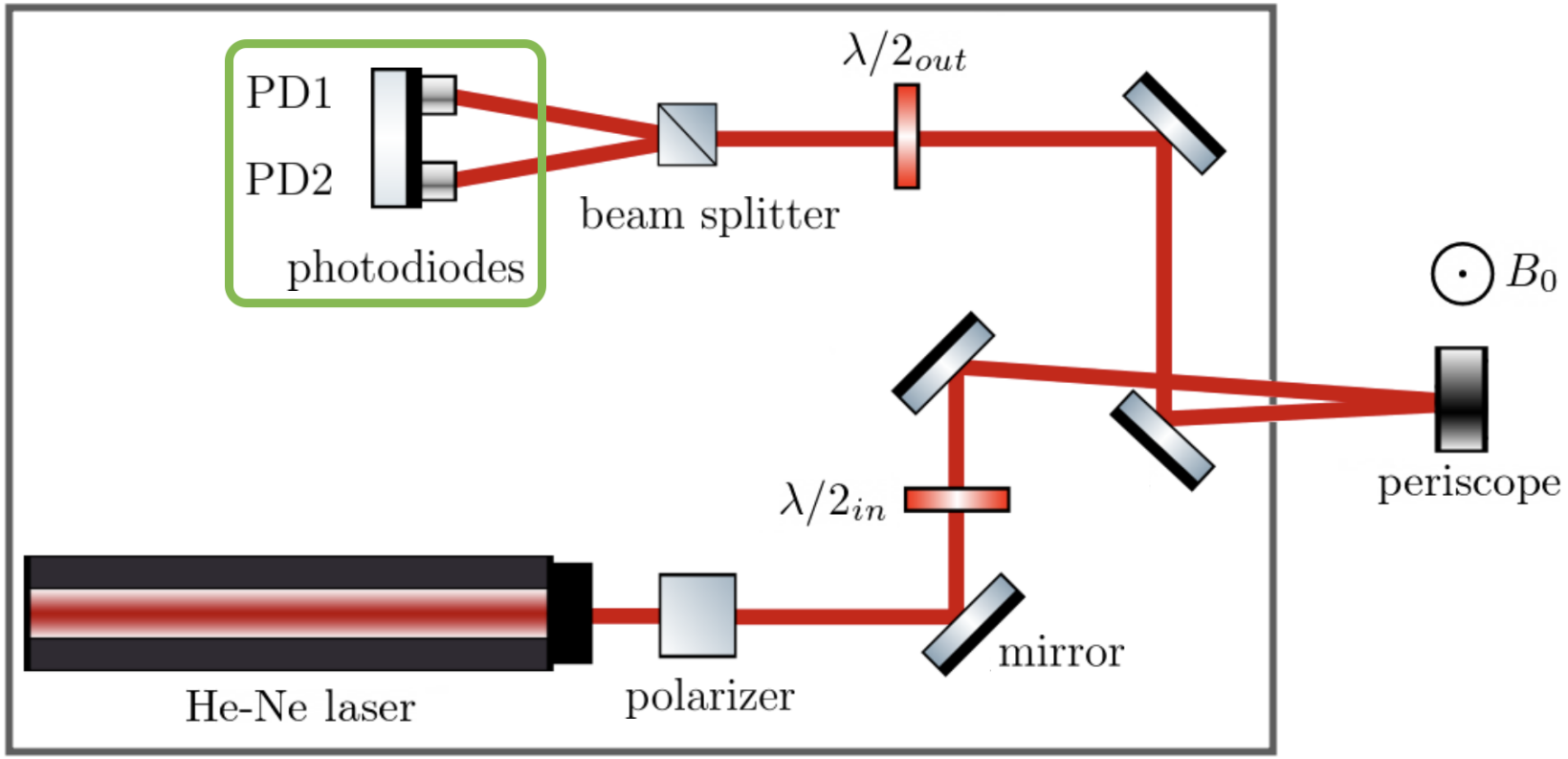
- Periscope: necessary to bring the laser light along the vertical direction and between the plates of the kicker

Setup scheme



- Beam splitter: incident light → two orthogonally-polarized beams
- $\lambda/2_{out}$: in absence of magnetic field, is fixes the laser polarization at 45°

Setup scheme



- $B = 0 \Rightarrow 45°$ polarization $\Rightarrow V_{\text{diffPD}} = V_{PD1} - V_{PD2} = 0$
- $B \neq 0 \Rightarrow V_{\text{diffPD}} \propto B$

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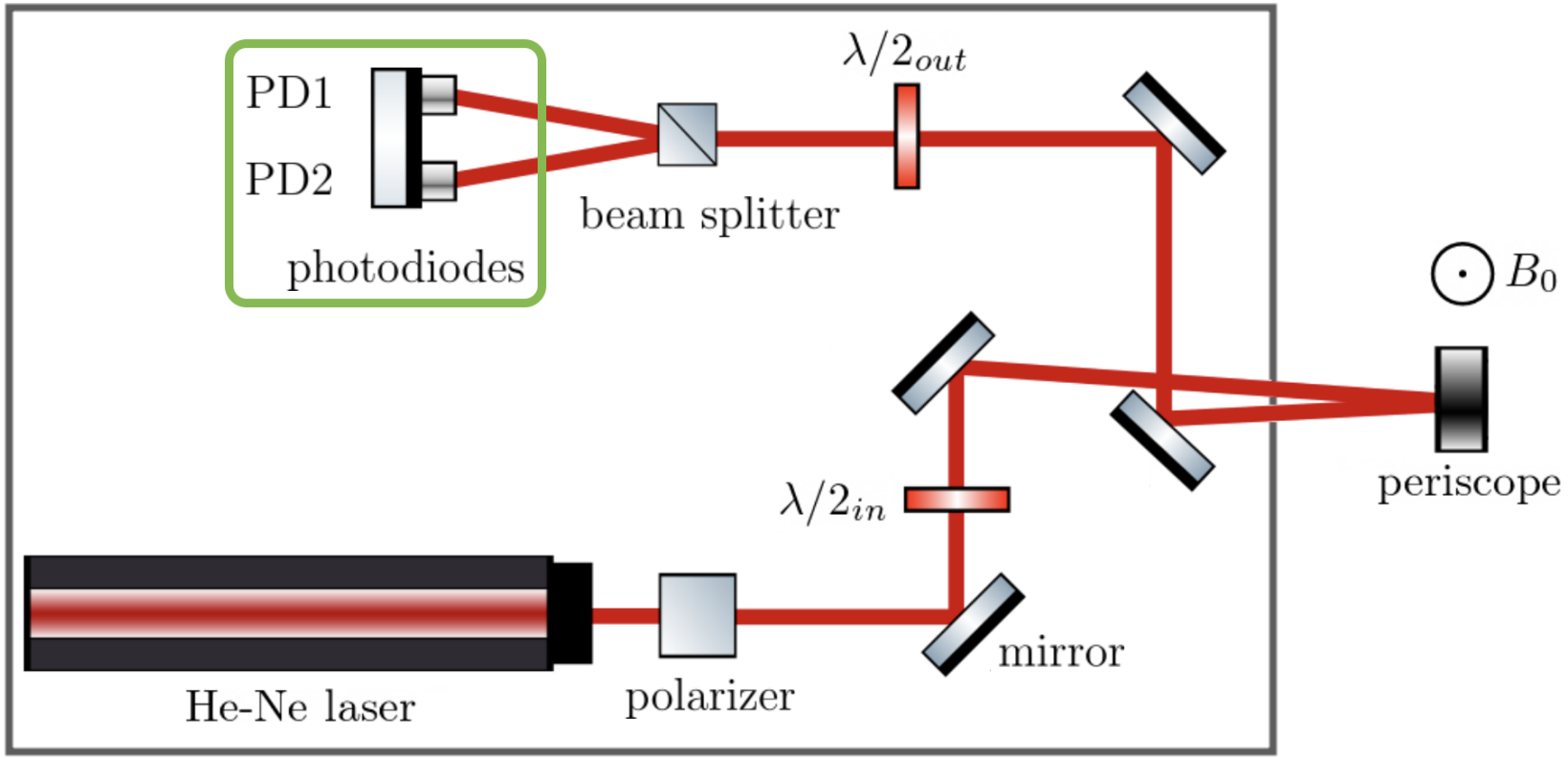

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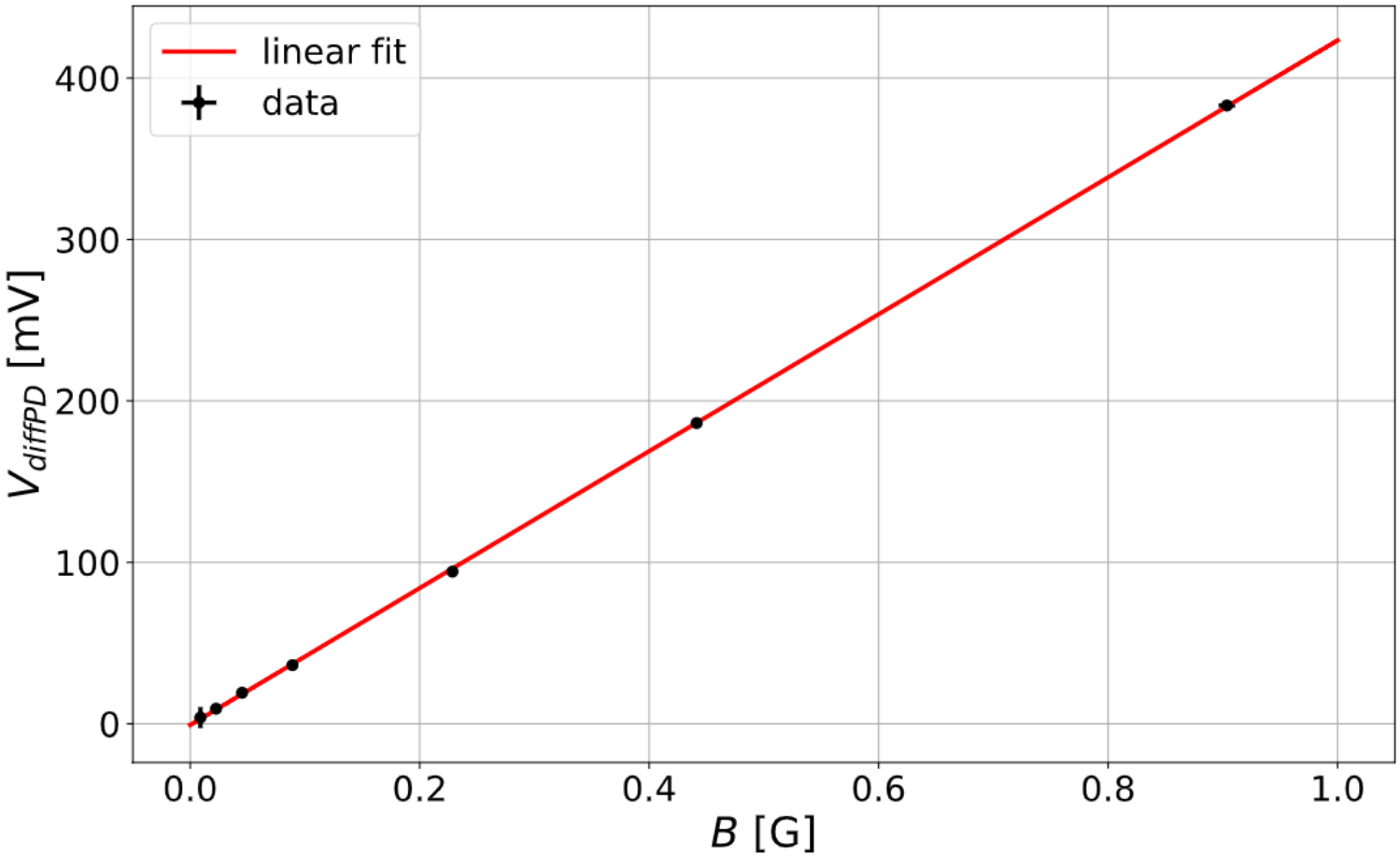
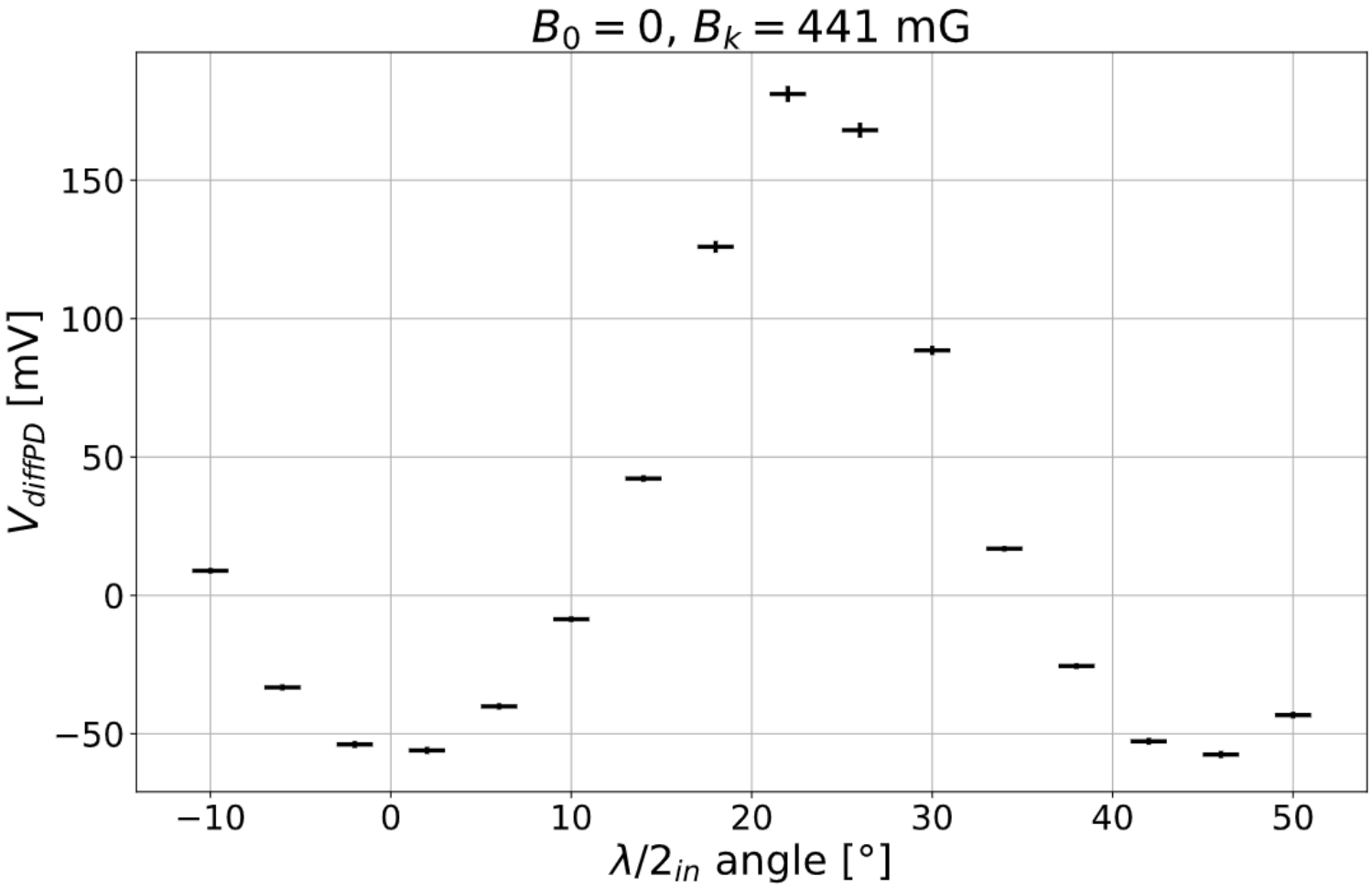
Calibration



$$\frac{dV_{\mathrm{diffPD}}}{dB} = (424 \pm 1)\,\mu\mathrm{V}\,\mathrm{mG}^{-1}$$

How to choose the initial polarization?

We choose the value of $\lambda/2_{in}$ that maximizes the Faraday effect.



Magnetometer simulation: Jones formalism

- The polarization state is represented by a 2D vector:

$$\mathbf{E}_{in} = \begin{pmatrix} E_{0x} e^{i\phi_{0x}} \\ E_{0y} e^{i\phi_{0y}} \end{pmatrix}$$

- Optical elements effect represented by 2×2 matrices:

$$\mathbf{J}_M = \begin{pmatrix} e^{i\delta_x} & 0 \\ 0 & e^{i\delta_y} \end{pmatrix}, \mathbf{J}_{\lambda/2}(\theta) = \begin{pmatrix} \cos(2\theta) & \sin(2\theta) \\ \sin(2\theta) & -\cos(2\theta) \end{pmatrix}, \underbrace{\mathbf{J}_X = \begin{pmatrix} \cos\Phi & \sin\Phi \\ -\sin\Phi & \cos\Phi \end{pmatrix}}_{\Phi = V(B_0 + B_k)l}$$

- The Jones vector associated with the laser going through the magnetometer can be computed as:

$$\mathbf{E}_{out} = \mathbf{J}_{\lambda/2}(\theta_{out}) \cdot \mathbf{J}_M \cdot \mathbf{J}_M \cdot \widetilde{\mathbf{J}}_X(B_0, B_k) \cdot \mathbf{J}_M \cdot \mathbf{J}_{\lambda/2}(\theta_{in}) \cdot \mathbf{J}_M \cdot \mathbf{E}_{in} = \begin{pmatrix} E_x e^{i\phi_x} \\ E_y e^{i\phi_y} \end{pmatrix}$$

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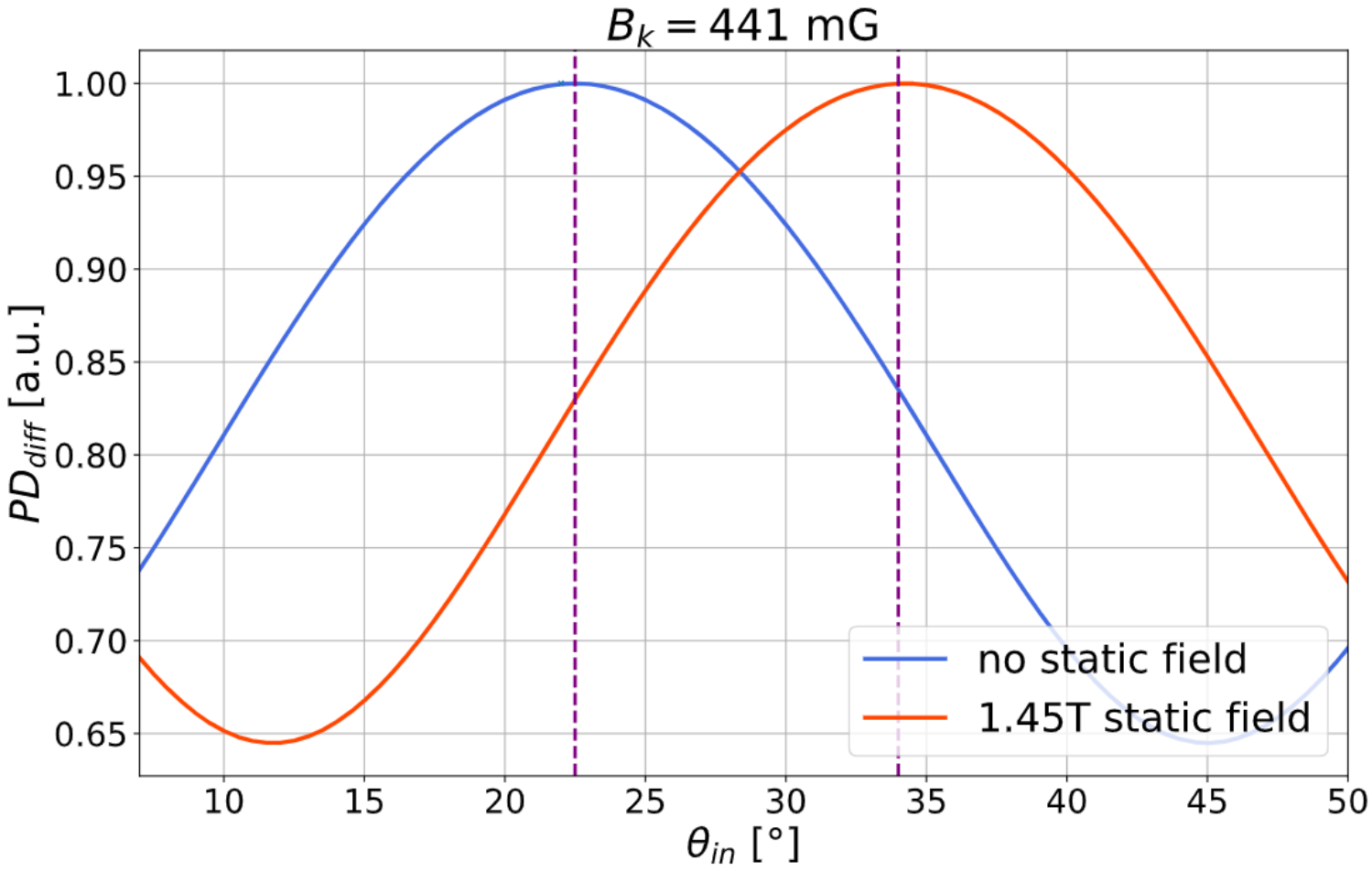
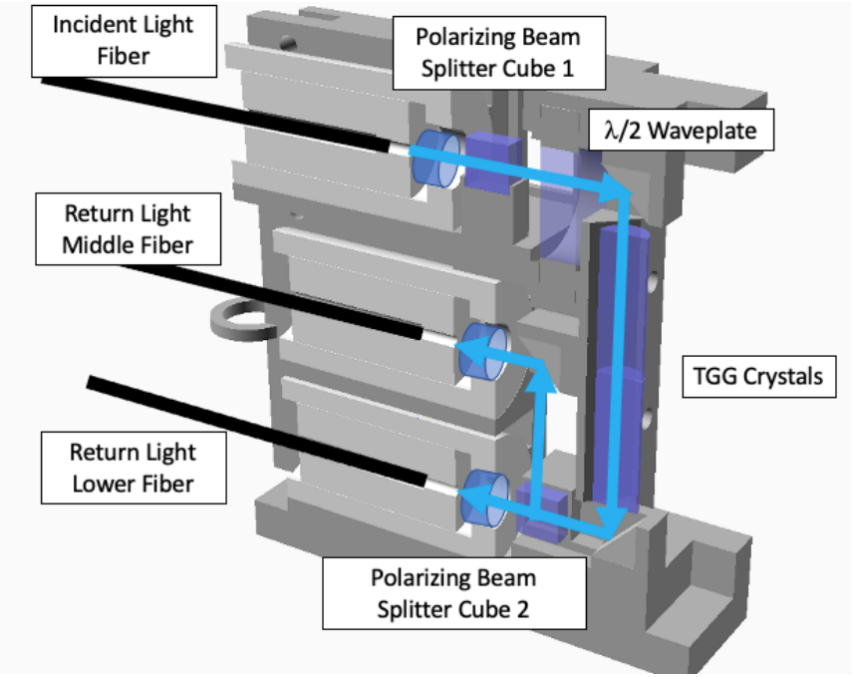
What if there's an additional strong static field?

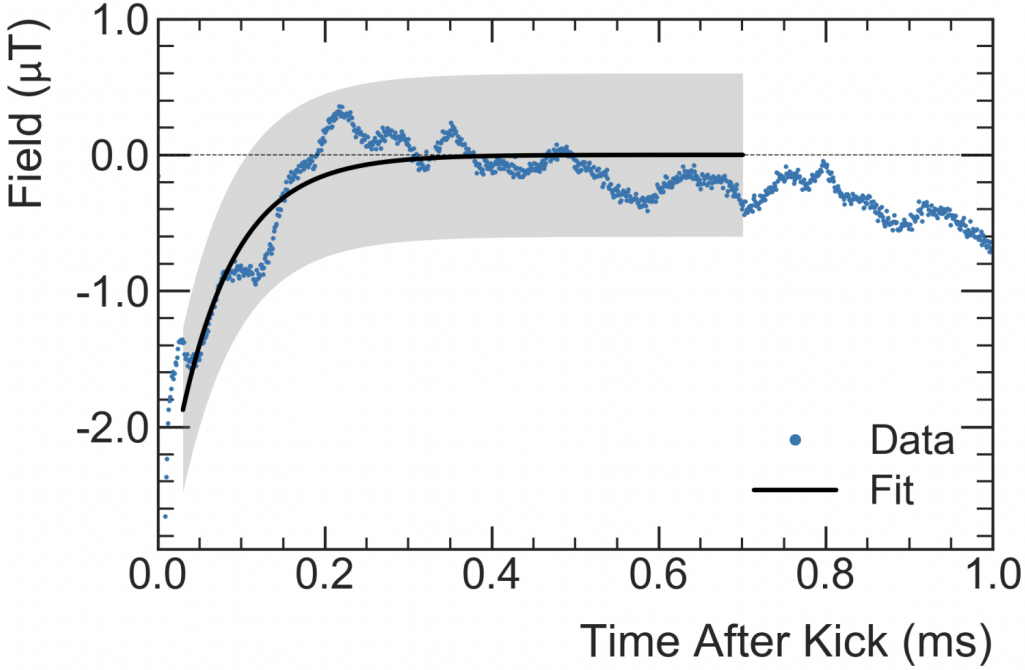
The angle of polarization that optimizes the Faraday effect changes.



Run 1 results

A fiber magnetometer was built by the Argonne National Laboratory group ($s = 6.87\,\mathrm{mV\,G^{-1}}$):





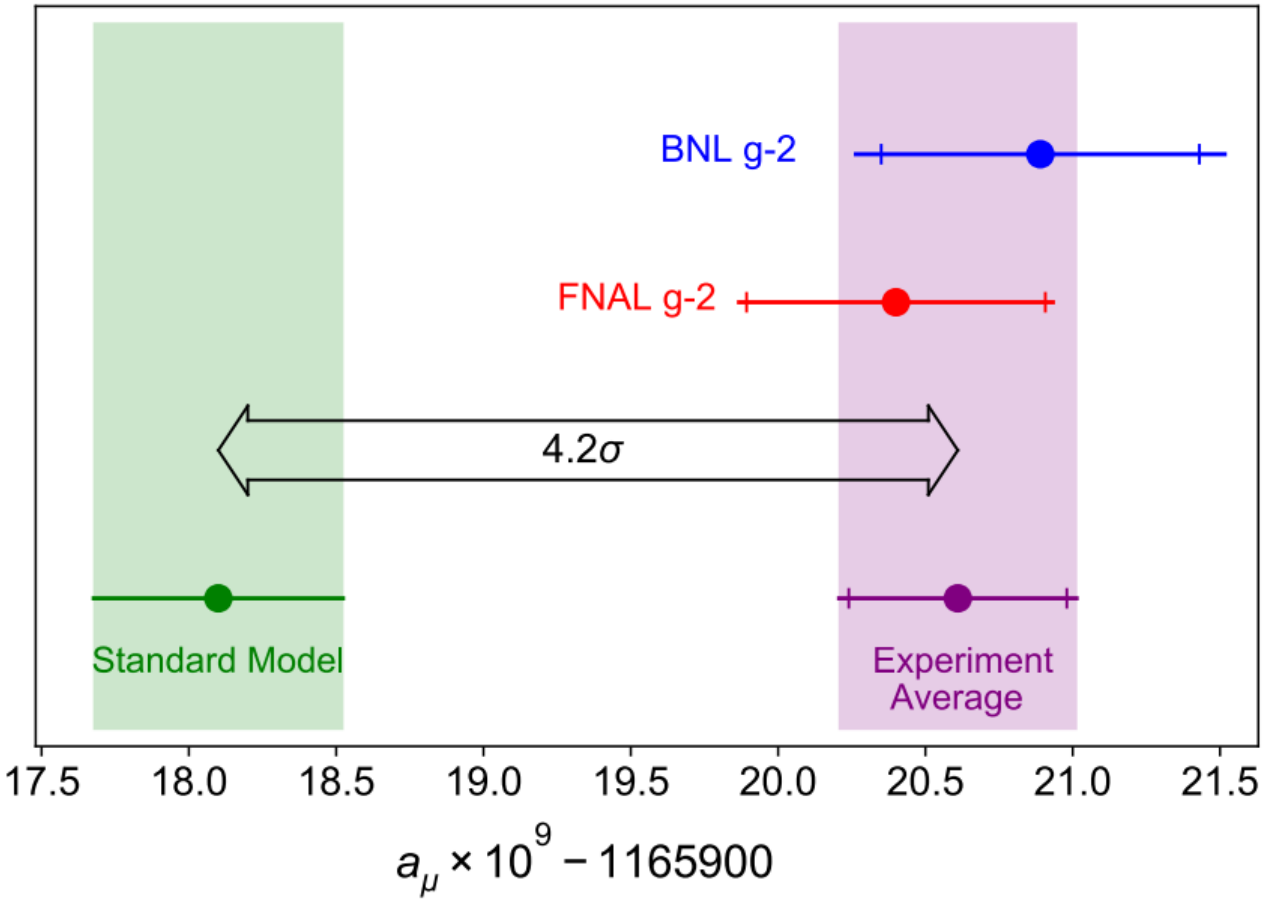
$$B_{EC}(t) = B_{EC}\exp[-(t-t_0)/\tau_{EC}]$$

$$B_{EC} = -(18.7 \pm 2.5)\,\mathrm{mG},\ \tau_{EC} = (68 \pm 15)\,\mu\mathrm{s} \quad \Rightarrow \quad b_{EC} = -(27 \pm 37)\ \mathrm{ppb}$$

Conclusions

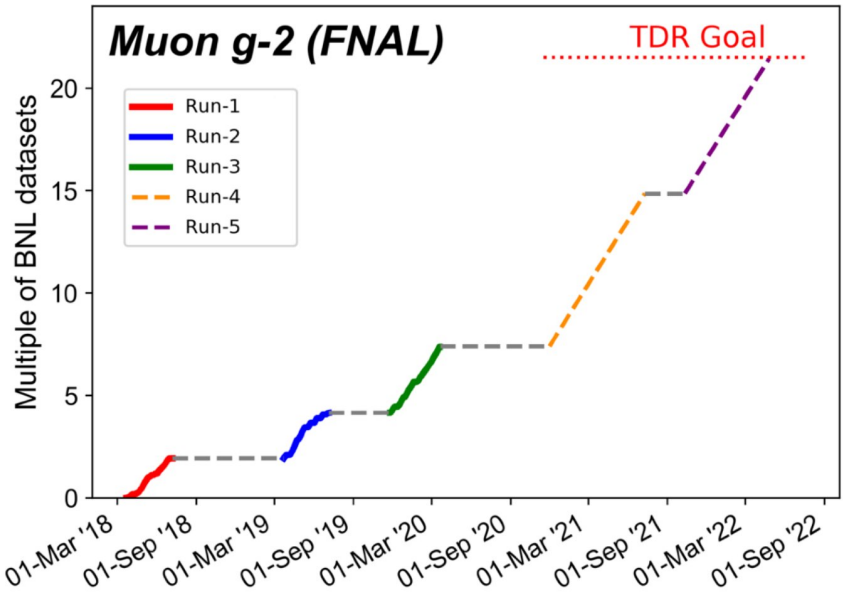
a_μ Run 1 result

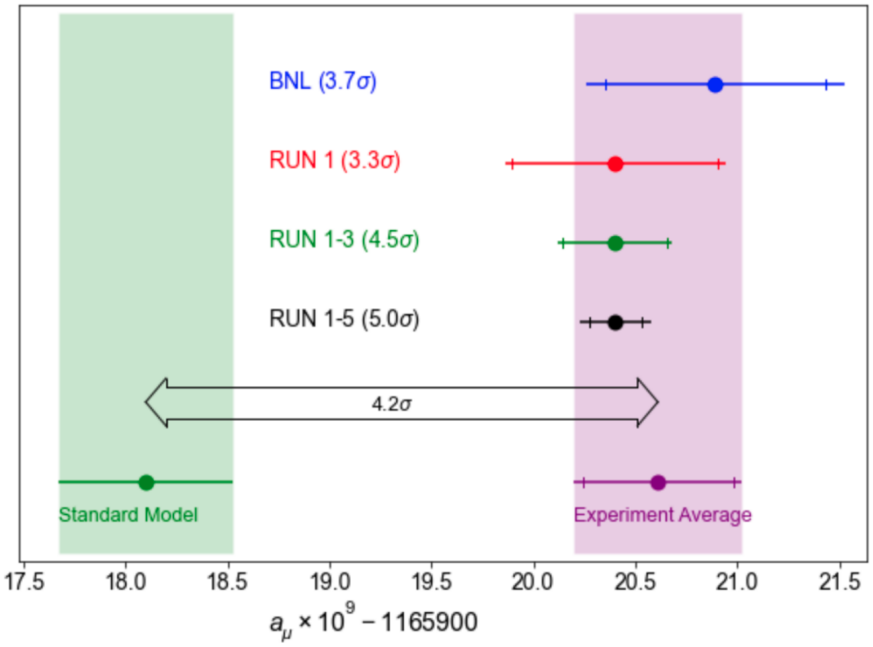
The significance of the discrepancy between the measured and SM predicted a_μ increased from to 3.7σ to 4.2σ



Future prospects

- E989: better statistical and systematic precision in the next runs





- Experiments with different techinques → J-PARC E34 experiment
- Measurement of a_μ^{HLO} → MUonE Experiment at CERN

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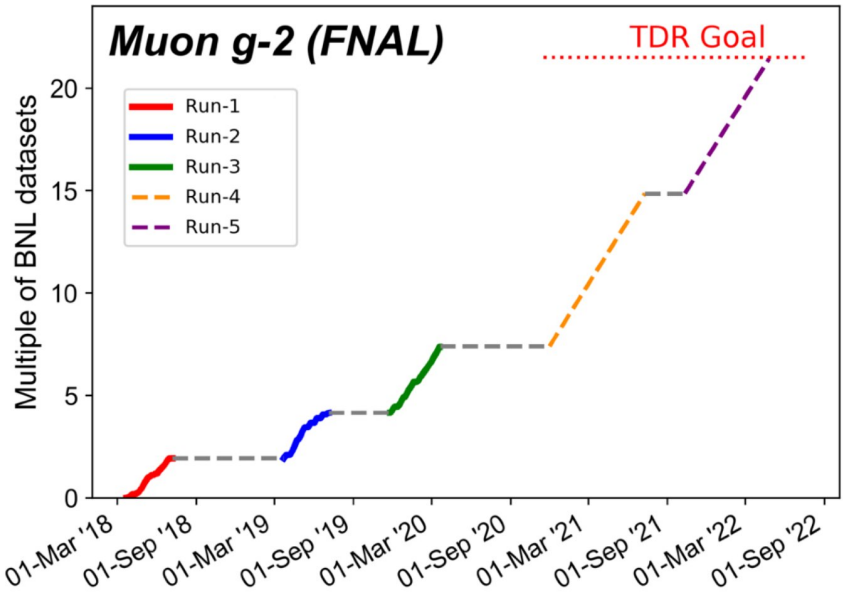

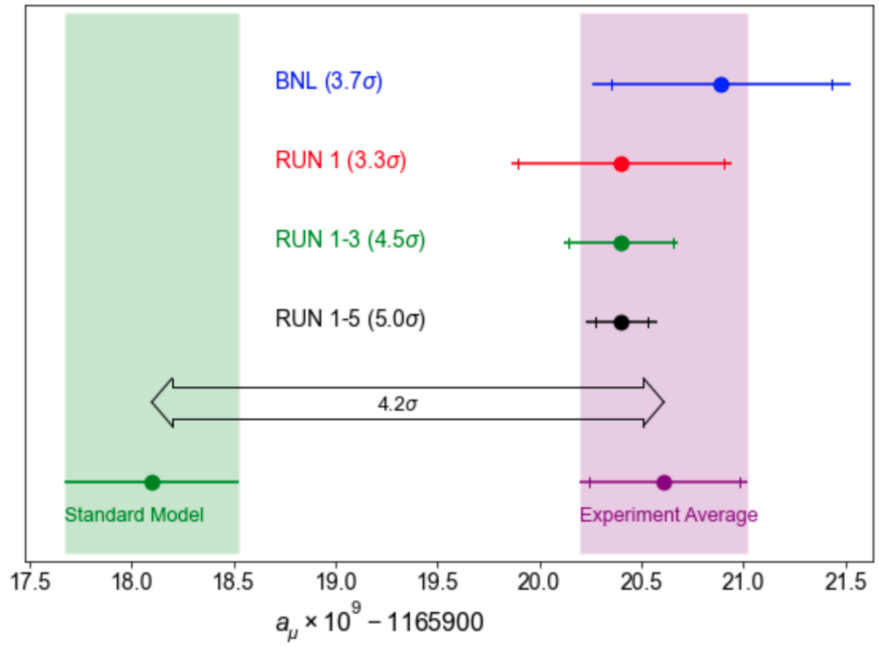

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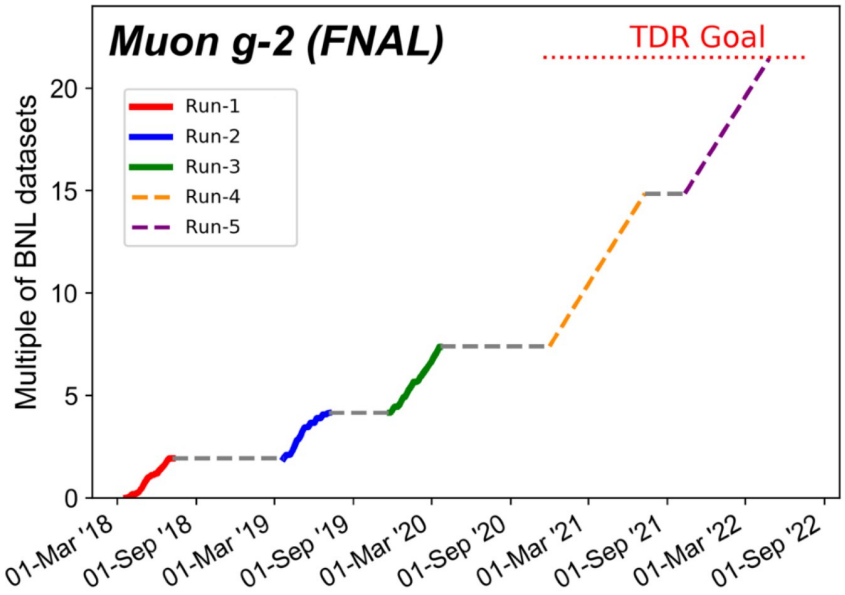

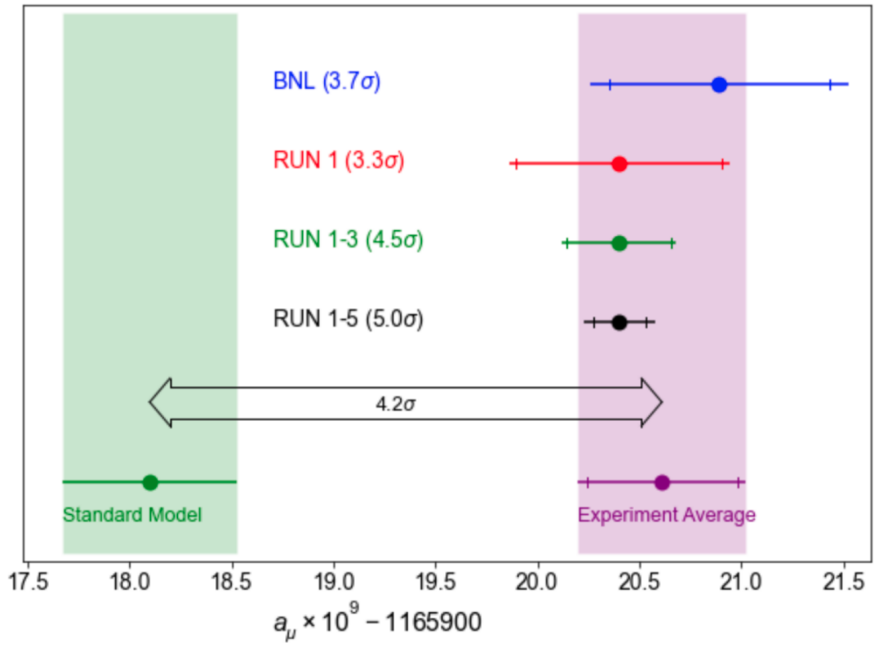

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Thanks for the attention!