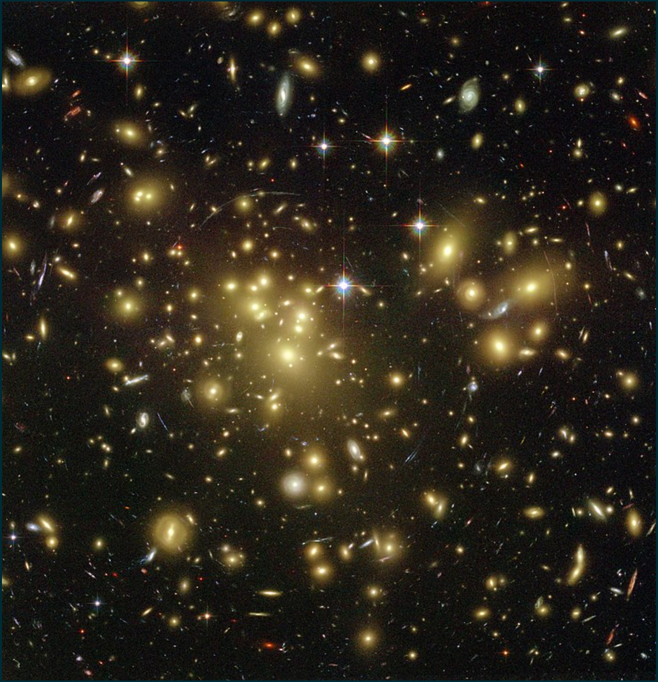
The magic is always in the details

The search for new physics with the muon

Alexander Voigt

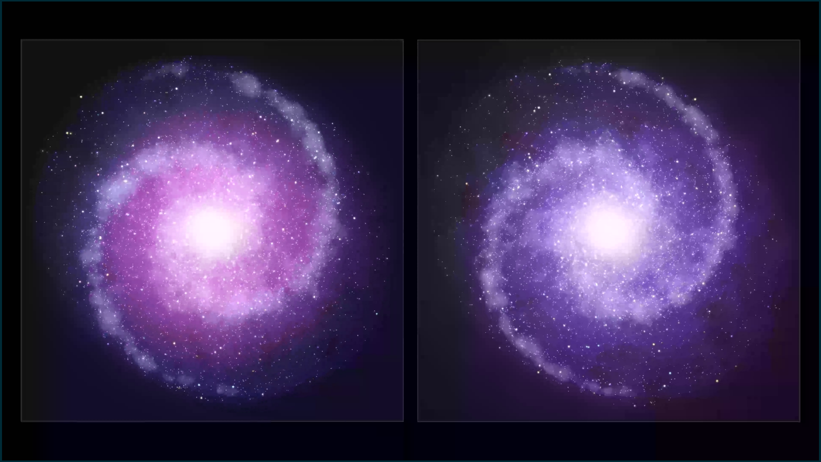
Hochschule Flensburg

Planetarium Talks 2022



[1]


[2]

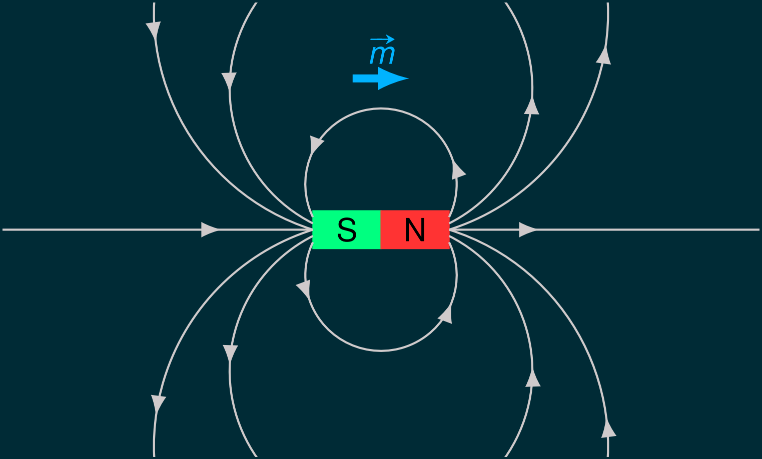


[3]

Magnetism

[4]

Magnetism: magnetic moment $\vec{m}$



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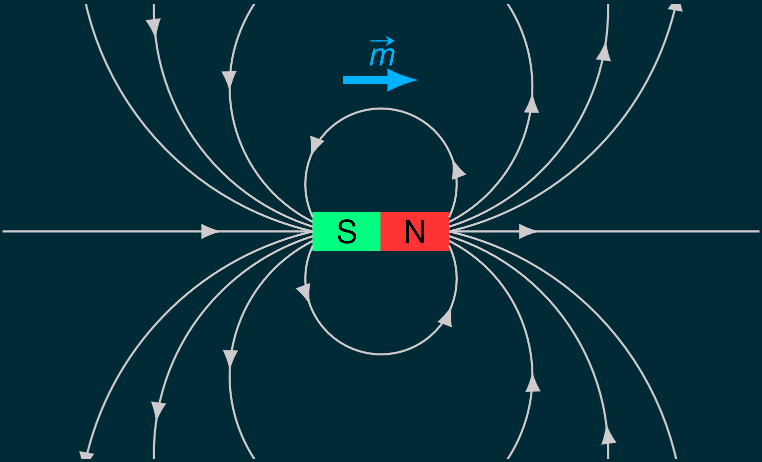

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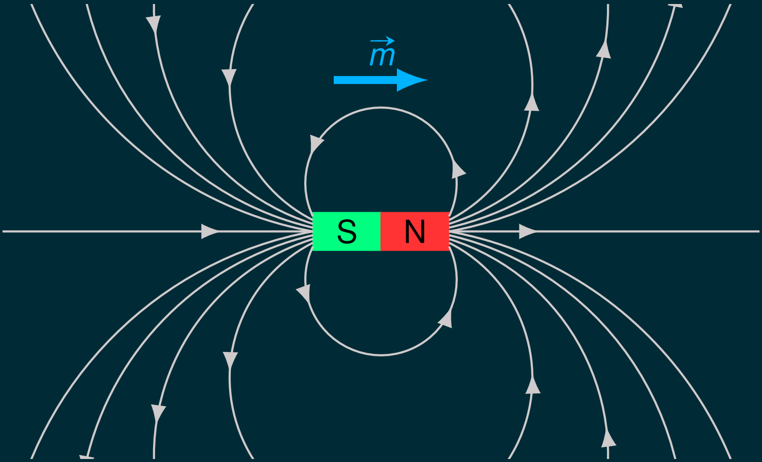
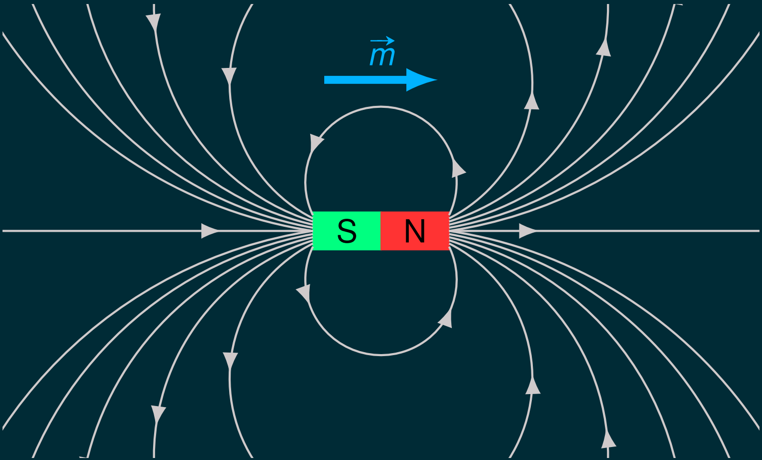


Magnetism: magnetic moment $\vec{m}$



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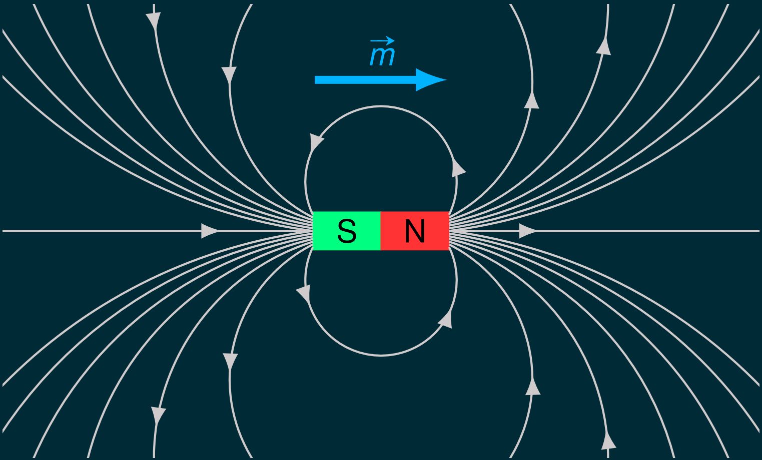

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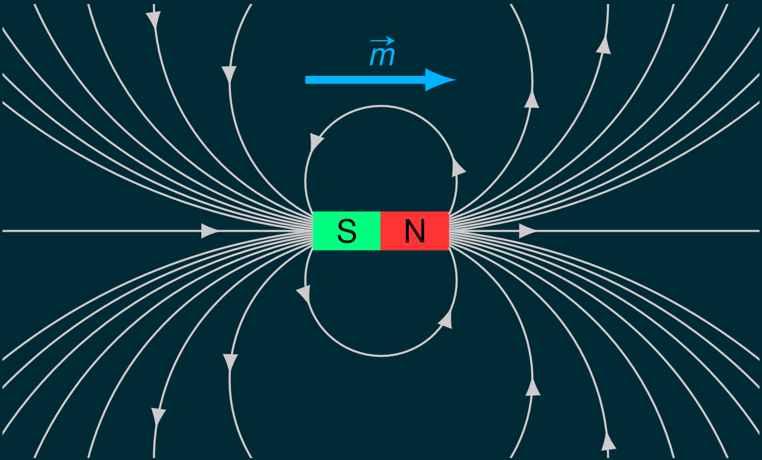

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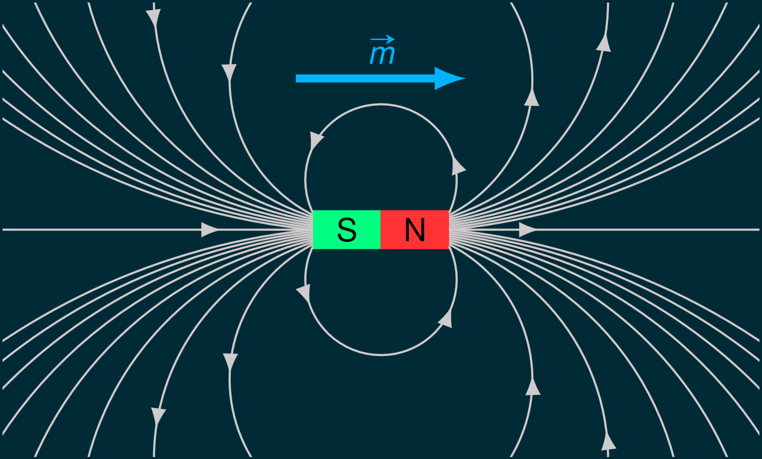

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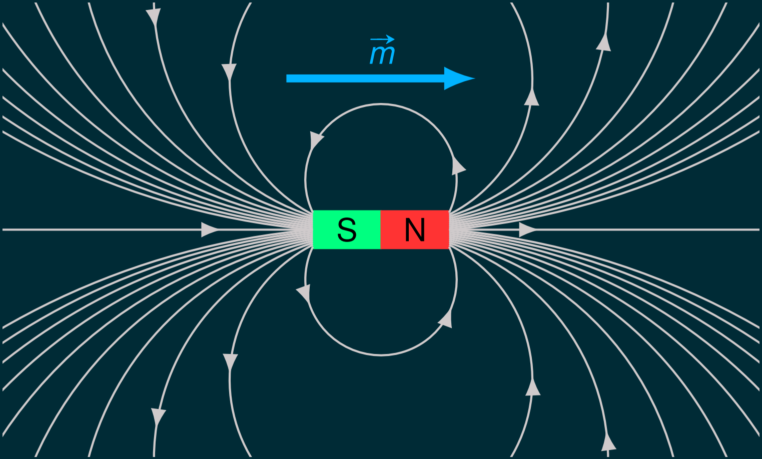

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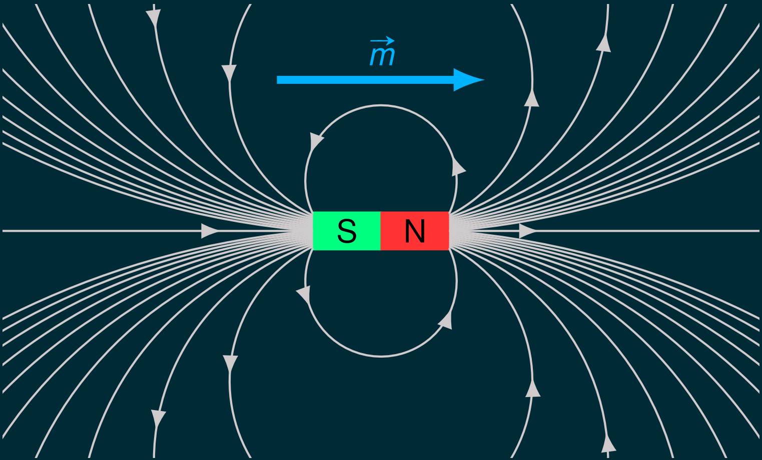

Magnetism: origin

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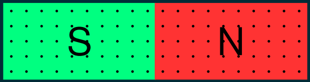

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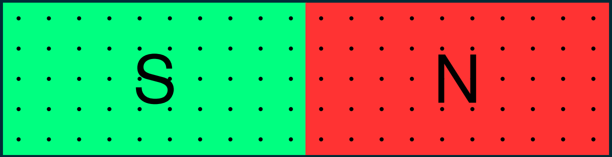

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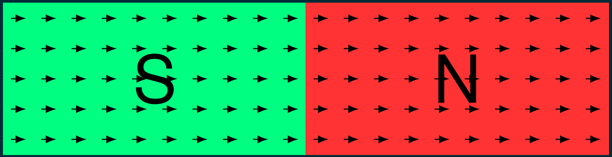
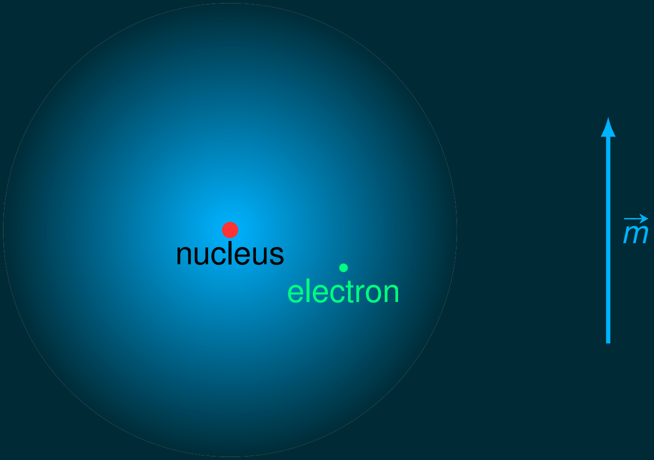
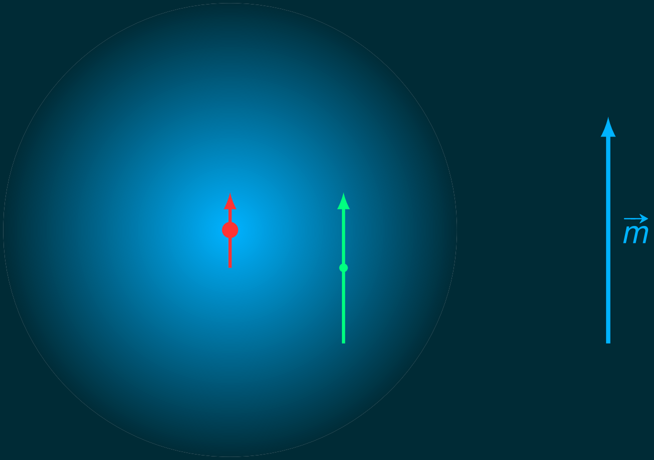


Magnetism: origin



Magnetism: origin



Electron g-factor

Magnetic moment of the electron:

$$\vec{m}_e = g_e \frac{e}{2m_e} \vec{S}$$

Measurement vs. prediction from classical Quantum Mechanics:

$$g_e^{\text{Exp}} = 2.002\,319\,304\,361\,46(58)$$

Electron *g*-factor

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Measurement vs. prediction from classical Quantum Mechanics:

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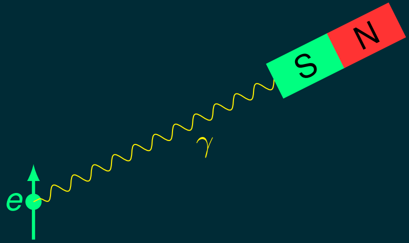
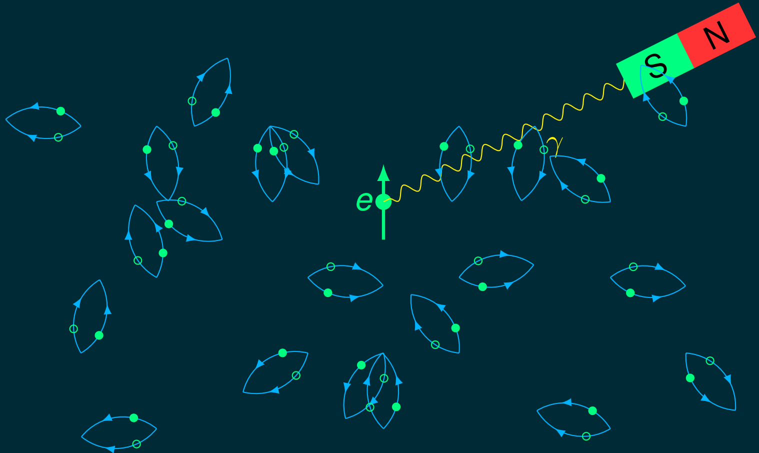
$$g_e^{\text{QM}} = 2$$

Gigantic disagreement!

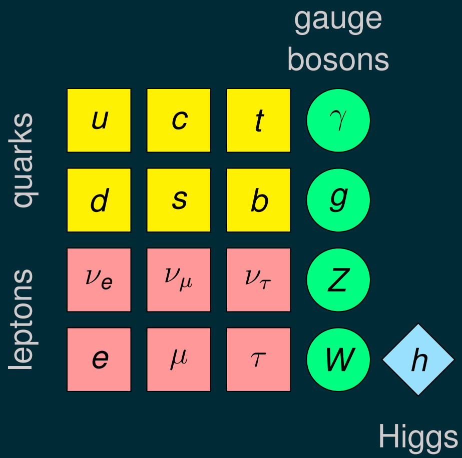
Electron *g*-factor: Quantum Corrections



Electron *g*-factor: Quantum Corrections

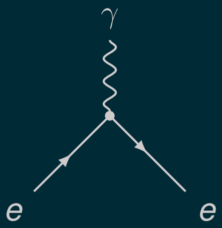


The Standard Model of Particle Physics



Electron *g*-factor: Quantum Corrections

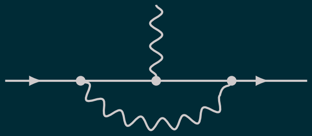
Direct interaction of an electron with a magnetic field (mediated by a photon):



$\Rightarrow \qquad g_e = 2$

Electron *g*-factor: Quantum Corrections

Next order (1-loop) quantum correction:



$$g_e^{\text{1-loop}} \approx 2.002\,322\,82$$

[Schwinger 1948]

Relative deviation:

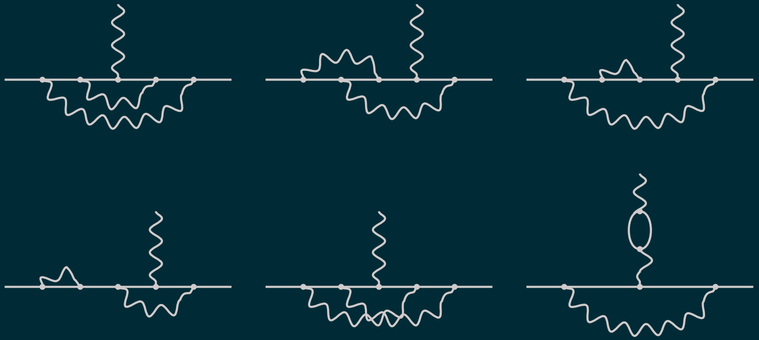
$$a_e^{\text{1-loop}} := \frac{g_e^{\text{1-loop}} - 2}{2} \approx 0.001\,161\,41$$

Electron *g*-factor: Quantum Corrections

[5]

Electron *g*-factor: Quantum Corrections

Quantum corrections with 2 loops:



$$a_e^{\text{2-loop}} \approx -0.000\,001\,772\,31$$

Electron g-factor

Comparison measurement vs. multi-loop prediction for a_e:

$$a_e^{\text{Exp}} = (11\,596\,521\,807.3 \pm 2.8) \times 10^{-13}$$

$$a_e^{\text{SM}} = (11\,596\,521\,816.4 \pm 7.7) \times 10^{-13}$$

Electron g-factor

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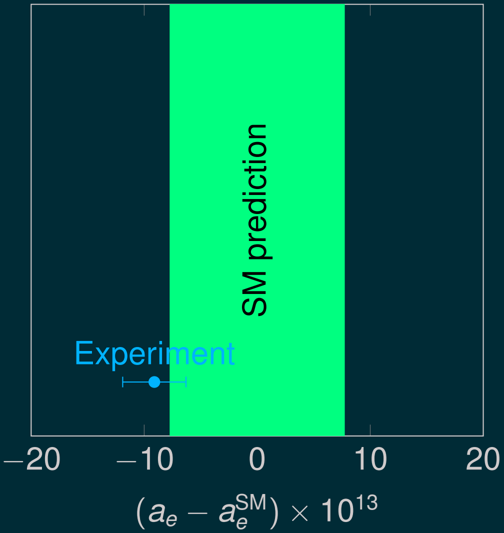
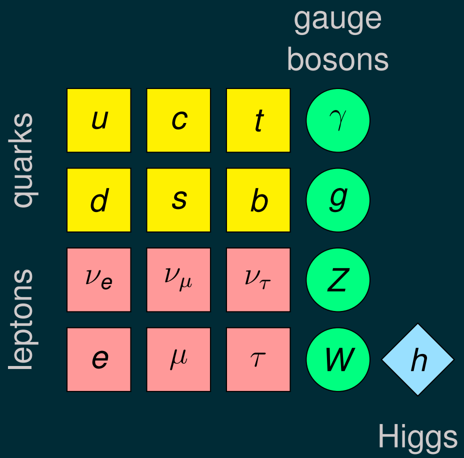
Agreement within a relative uncertainty of $\approx 10^{-10}$

Electron *g*-factor



$a_e^{\mathrm{Exp}} - a_e^{\mathrm{SM}} = (-9.1 \pm 8.2) \times 10^{-13}$

Muon g-factor

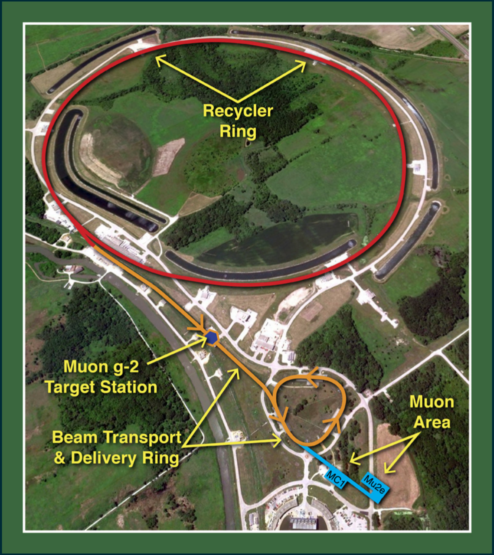


Muon g-factor

Standard Model multi-loop prediction:

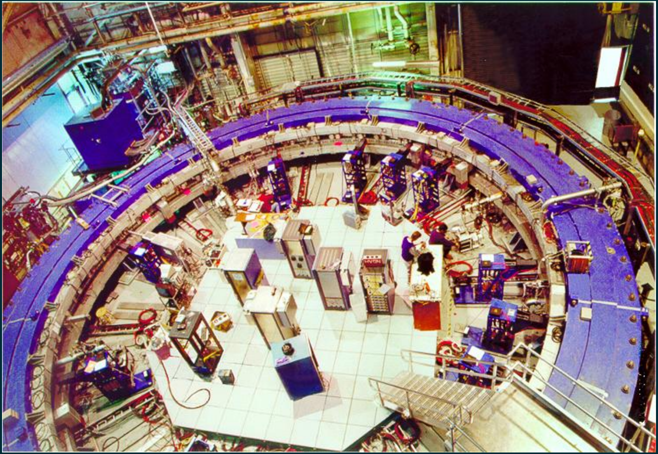
$$a_\mu^{\text{SM}} = (11\,659\,181.0 \pm 4.3) \times 10^{-10}$$
$$a_\mu^{\text{Exp}} = ?$$

Measurement: Fermilab (FNAL)



[FNAL]

Measurement: BNL



[6]

Measurement: at Fermilab (FNAL)

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Measurement: at Fermilab (FNAL)

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Measurement: at Fermilab (FNAL)

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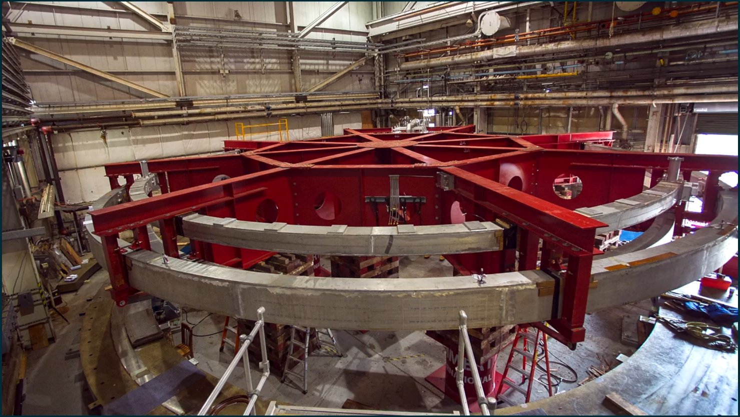
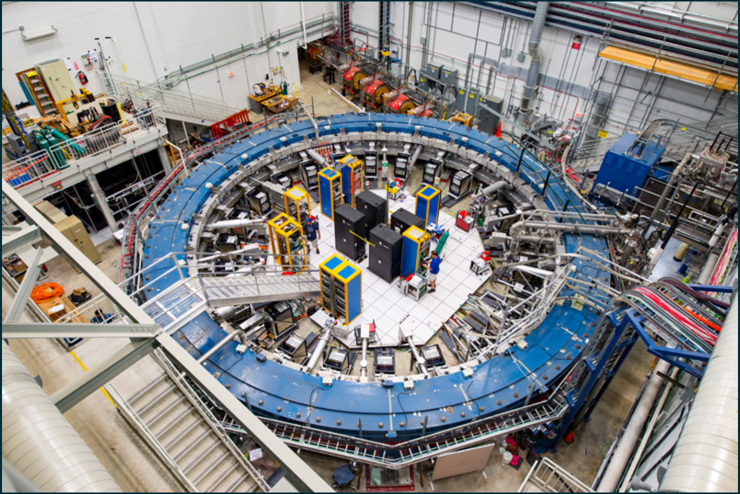
Measurement: Fermilab (FNAL)



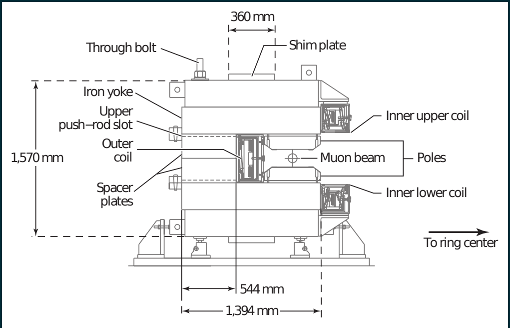
[10]

Measurement: Fermilab (FNAL)

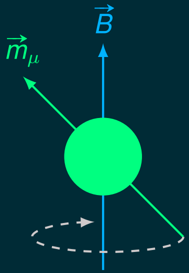


[11]

Measurement: Fermilab (FNAL)

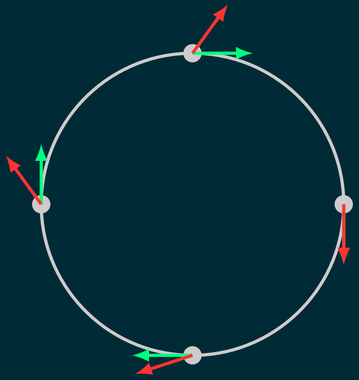


[12]



Measurement

Measure the deviation of the muon's spin precession frequency from the cyclotron frequency:

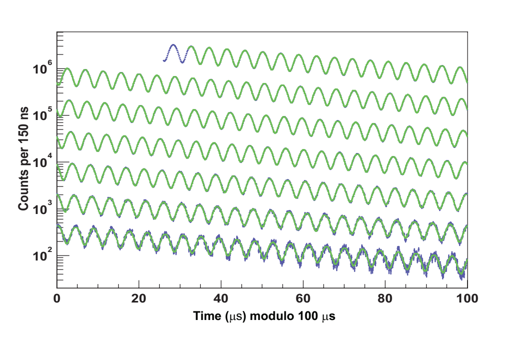


Measurement: Fermilab (FNAL)

Inside the ring the muons decay:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Energy of e^+ depends on muon's spin direction $\rightarrow$ infer a_μ



[13]

Measurement

Experimental measurements:

$$a_\mu^{\text{CERN}} = (11\,659\,229 \pm 81) \times 10^{-10} \qquad (1979)\ [14]$$

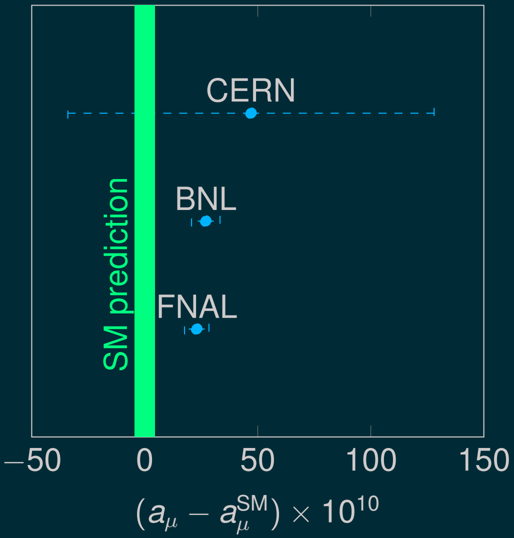
$$a_\mu^{\text{BNL}} = (11\,659\,208.0 \pm 6.3) \times 10^{-10} \qquad (2006)\ [15]$$

$$a_\mu^{\text{FNAL}} = (11\,659\,204.0 \pm 5.4) \times 10^{-10} \qquad (2021)\ [16]$$

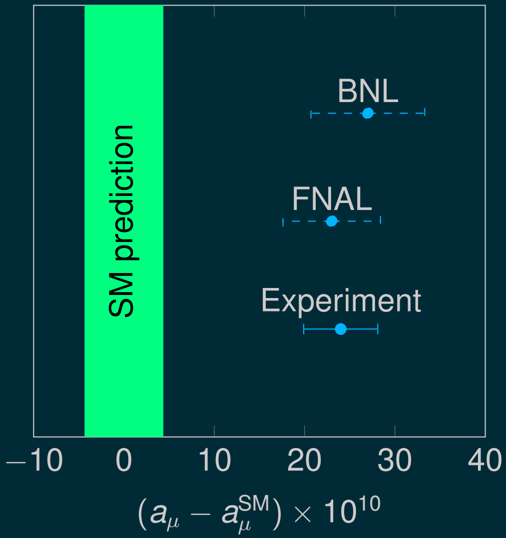
Combined:

$$a_\mu^{\text{Exp}} = (11\,659\,206.1 \pm 4.1) \times 10^{-10} \qquad (2021)\ [16]$$

Comparison of measurement and prediction



Comparison of measurement and prediction

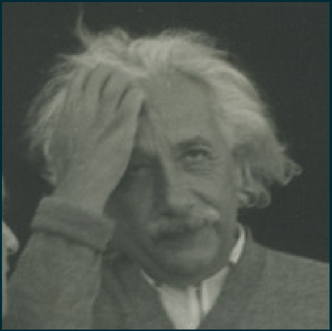


$a_\mu^{Exp} - a_\mu^{SM} = (25.1 \pm 5.9) \times 10^{-10}$

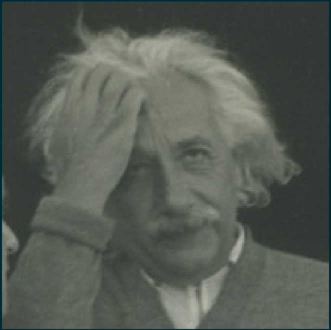
Deviation $\approx 4.2\sigma$

$P(\text{data}|\text{SM}) \approx 0.0027\%$

Where does the deviation come from?


[17]

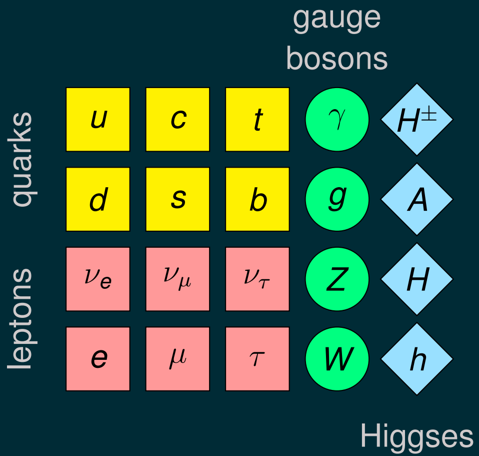
Where does the deviation come from?

 [17]

Maybe there are more particles, which we have not observed yet?

Where does the deviation come from?

Maybe there are more Higgs bosons?

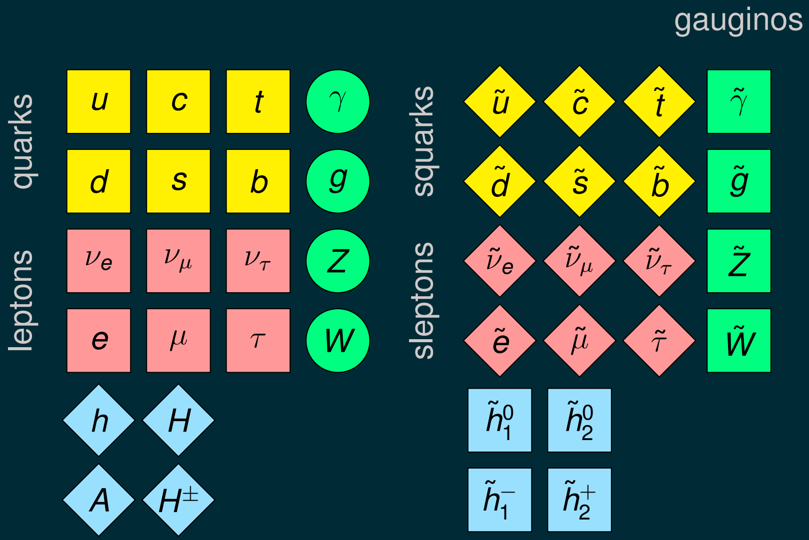


Two-Higgs Doublet Model

New quantum corrections in the 2HDM with 1 loop:

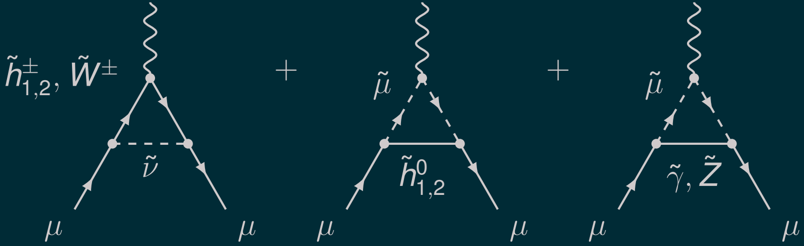
Minimal Supersymmetry

Maybe there is a spin-partner for each particle?



Minimal Supersymmetry

New quantum corrections in the Minimal Supersymmetric Standard Model (MSSM) with 1 loop:



Summary

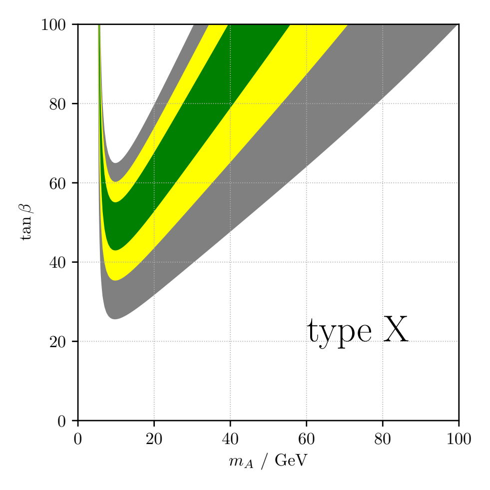
- a_μ describes the interaction strength of the muon's spin with a magnetic field
- a_μ is governed by quantum corrections
- 4.2σ discrepancy between prediction and measurment

$\Rightarrow$ hints to new, unknown particles

Let's wait for more data!

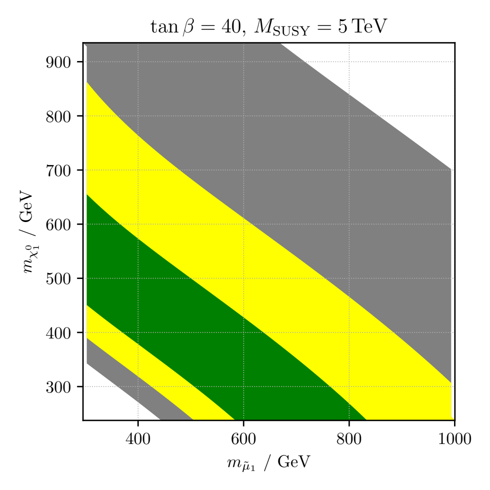
Backup

Two-Higgs Doublet Model



[18]

Minimal Supersymmetry



Spin rotation frequencies

Lamor frequency:

$$\omega_S = -g\frac{Qe}{2m}B - (1-\gamma)\frac{Qe}{\gamma m}B$$

Cyclotron frequency:

$$\omega_C = -\frac{Qe}{\gamma m}B$$

Measure difference:

$$\omega_a = \omega_S - \omega_C = -\frac{g-2}{2}\frac{Qe}{m}B = -a\frac{Qe}{m}B$$

References I

[1] Hubble. *Abell 1689*. http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/01/image/a. Jan. 2003.

[2] Hubble. *M101*. http://hubblesite.org/newscenter/newsdesk/archive/releases/2006/10/image/a. Feb. 2006.

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[5] Jacob Bourjaily. *Julian Schwinger headstone*. https://commons.wikimedia.org/wiki/File:Julian_Schwinger_headstone.JPG. Apr. 2013.

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[6] `https://www.g-2.bnl.gov/pictures/index.html`.

[7] *The Big Move*. Dominik Stöckinger, “Neues aus der Teilchenphysik – Spektakuläres Ergebnis des Myon g-2 Experiments und seine Folgen”, Lange Nacht der Wissenschaften, 2021.

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[11] *Muon g-2 Experiment*. https://vms.fnal.gov/asset/detail?recid=1950114. Aug. 2017.

[12] James P. Miller u. a. "Muon (g-2): Experiment and Theory". In: *Ann. Rev. Nucl. Part. Sci.* 62 (2012), S. 237–264. DOI: 10.1146/annurev-nucl-031312-120340.

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[15] G. W. Bennett u. a. “Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL”. In: *Phys. Rev. D* 73 (2006), S. 072003. DOI: 10.1103/PhysRevD.73.072003. arXiv: hep-ex/0602035.

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[16] B. Abi u. a. “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm”. In: *Phys. Rev. Lett.* 126 (14 Apr. 2021), S. 141801. DOI: 10.1103/PhysRevLett.126.141801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.126.141801.

References X

[17] *Albert Einstein scratching his head: with Jakob Klatzkin (left) and Abraham S. Yahuda (right) in Saranac Lake*. https://www.lbi.org/griffinger/record/243953. Aug. 1941.

References XI

[18] Peter Athron u. a. “Two-loop prediction of the anomalous magnetic moment of the muon in the Two-Higgs Doublet Model with GM2Calc 2”. In: *Eur. Phys. J. C* 82.3 (2022), S. 229. DOI: 10.1140/epjc/s10052-022-10148-9. arXiv: 2110.13238 [hep-ph].