Searching for new bosons with precision spectroscopy of highly charged ions: *g*-factor and hyperfine structure tests

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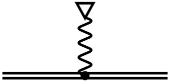
The bound-electron g factor

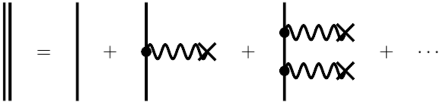
$$\text{Bound-electron } g \text{ factor theory} = \underbrace{\text{free } g \text{ factor theory}}_{\text{perturbative } B \text{ field}} + \underbrace{\text{Lamb shift theory}}_{\text{strong Coulomb field}}$$

For a Coulomb potential, the Dirac g-factor for the $1s$ state (G. Breit, 1928):



$$g_{\mathrm{D}} = \frac{2}{3}\left(1 + 2\sqrt{1-(Z\alpha)^2}\right) = 2 - \frac{2}{3}(Z\alpha)^2 - \frac{1}{6}(Z\alpha)^4 + \ldots$$

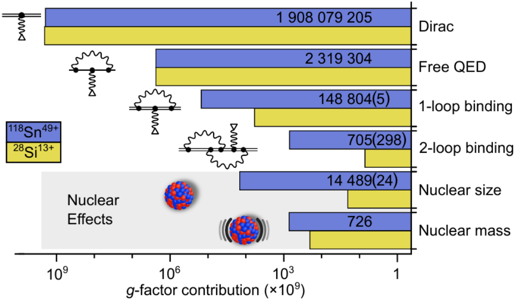
Double line: Coulomb-Dirac (wave function or) propagator:



with an arbitrary number of interactions with the nuclear potential

$\Rightarrow$ **See the talk of Bastian Sikora at the beginning of this session!**

g factor of hydrogenlike Sn^{49+}



$$g_{\rm exp} = 1.910\,562\,058\,962(73)_{\rm stat}(42)_{\rm sys}(910)^{1}_{\rm ext}\,;$$

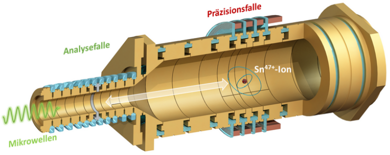
$$g_{\rm theo} = 1.910\,561\,82(30)^{1}$$

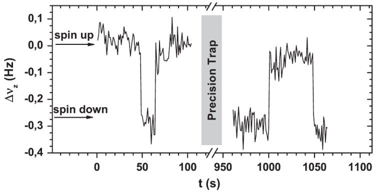
$$g_{\rm theo} = 1.910\,561\,98(4)^{2} \quad \text{improved two-loop QED theory}$$

[1] J. Morgner, B. Tu, C. M. König *et al.*, Nature **622**, 53 (2023);
S. G. Karshenboim, Phys. Lett. A **266**, 380 (2000);
V. A. Yerokhin, P. Indelicato, V. M. Shabaev, Phys. Rev. Lett. **89**, 143001 (2002)
K. Pachucki, U. D. Jentschura, V. A. Yerokhin, Phys. Rev. Lett. **93**, 150401 (2004);
R. N. Lee, A. I. Milstein, I. S. Terekhov, S. G. Karshenboim, Phys. Rev. A **71**, 052501 (2005)
A. Czarnecki, M. Dowling, J. Piclum, R. Szafron, Phys. Rev. Lett. **120**, 043203 (2018)
[2] B. Sikora, V. A. Yerokhin, C. H. Keitel, Z. H., Phys. Rev. Lett. **134**, 123001 (2025)

Penning trap measurements of the g factor

See talks of Jonathan Morgner and Anton Gramberg!





Larmor frequency:

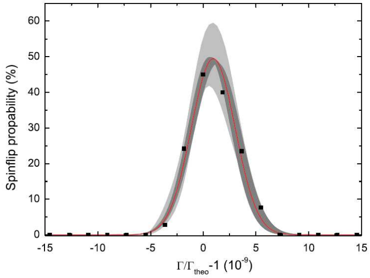
$$\nu_{\rm L} = g\mu_B B \frac{1}{2\pi} = g\frac{e}{4\pi m_e}B \,,$$

Cyclotron frequency:

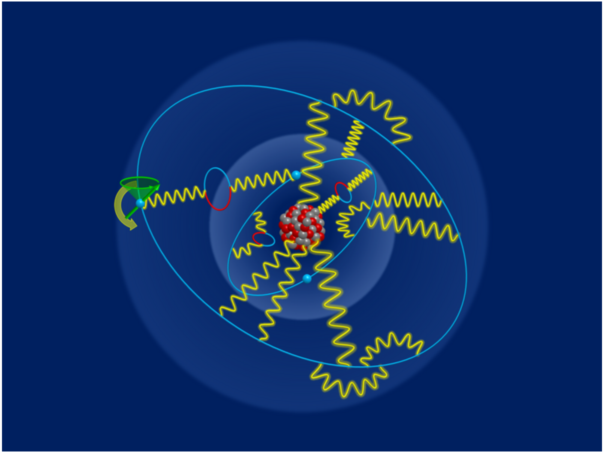
$$\nu_{\rm c} = \frac{qB}{2\pi m_{\rm ion}} \,, \quad \rightarrow \quad g_{\rm exp} = 2\frac{\nu_{\rm L}}{\nu_{\rm c}}\frac{m_e}{m_{\rm ion}}\frac{q}{e} \quad (1)$$

E.g. the ALPHATRAP experiment at the MPIK Heidelberg (S. Sturm, K. Blaum *et al.*);

HITRAP at GSI/FAIR Darmstadt; Uni Mainz



g factor of lithiumlike Sn^{47+}

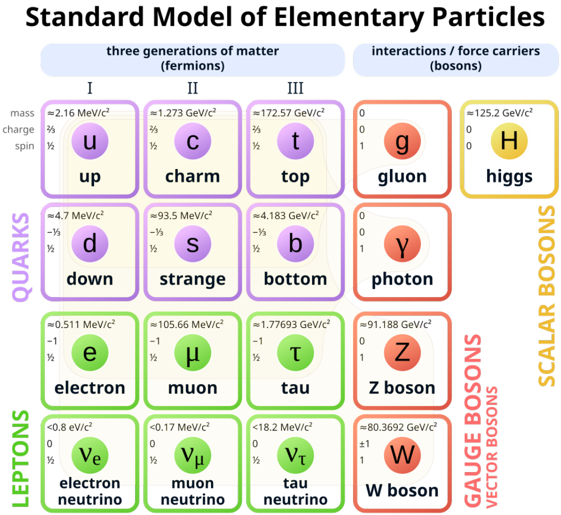


$$g_{\text{theo}} = 1.980\,354\,796(12)$$

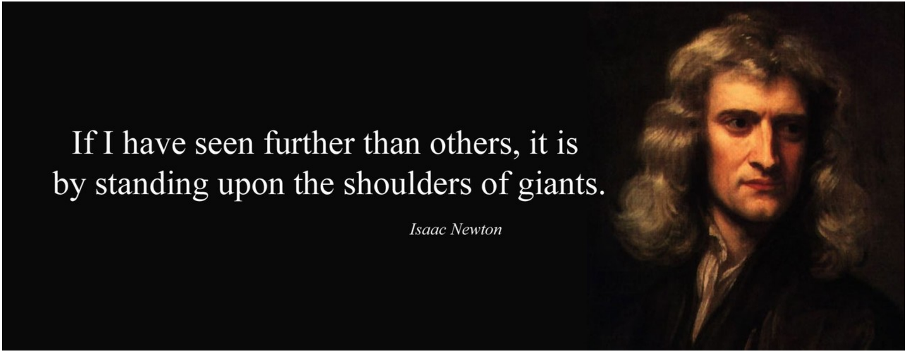
$$g_{\text{exp}} = 1.980\,354\,799\,750(84)_{\text{stat}}(54)_{\text{sys}}(944)_{\text{ext}}$$

J. Morgner, V. A. Yerokhin, C. König *et al.*, Science **388**, 6750, 945 (2025)

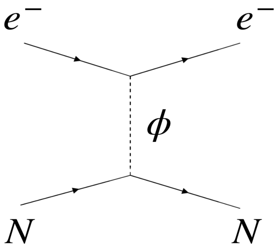
Beyond the Standard Model



However in Nature there should be something more, maybe new scalars or vectors?


If I have seen further than others, it is
by standing upon the shoulders of giants.
Isaac Newton

- A proposed fifth fundamental force
  Massive spinless boson ϕ (mass range unknown)
  Couples electrons to nucleons
- Relevance to high-energy physics
  - They are light dark matter candidates
  - Known to be addressable by low-energy experiments since their proposal:
    P. W. Graham, D. E. Kaplan, S. Rajendran, Phys. Rev. Lett. **115**, 221801 (2011)

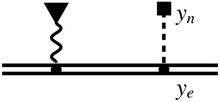


- Yukawa potential seen by electrons

$$V_\phi(\mathbf{r}) = -\hbar c\, \alpha_{\mathrm{NP}} \left\{ \begin{matrix} Z \\ A - Z \end{matrix} \right\} \frac{\mathrm{e}^{-\frac{m_\phi c}{\hbar}|\mathbf{r}|}}{|\mathbf{r}|}$$

  - m_ϕ: mass of the boson
  - $\frac{y_e y_p}{4\pi}$ or $\alpha_{\mathrm{NP}} = \frac{y_e y_n}{4\pi}$ coupling constant: coupling **electron-proton** or **electron-neutron**

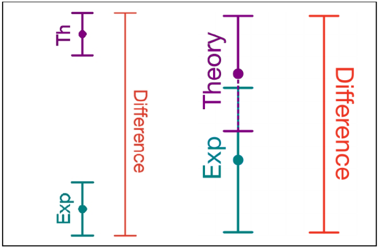
Correction to g factor:



$$\Delta g_{1s} = -\frac{4}{3}\alpha_{\mathrm{NP}}\frac{(Z\alpha)}{\gamma}A\left(1+\frac{m_\phi}{2Z\alpha m_e}\right)^{-2\gamma} \times \left[3-2\frac{(Z\alpha)^2}{1+\gamma}-\frac{2\gamma}{1+\frac{m_\phi}{2Z\alpha m_e}}\right]$$

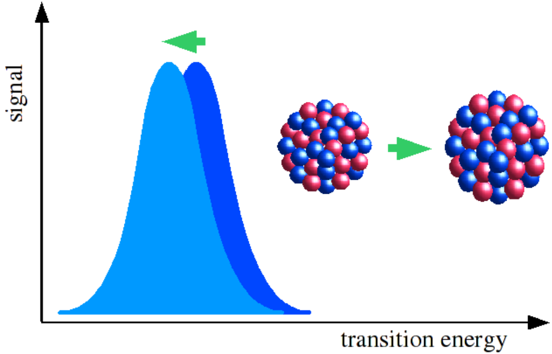
V. Debierre, Z.H., C. H. Keitel, Phys. Lett. B **807**, 135527 (2020)

If a disagreement between experiment and standard model theory is found, that MIGHT BE due to this term:

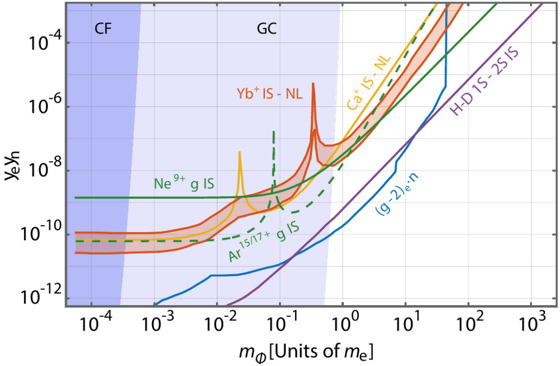


Recent **ALPHATRAP experiment** on the isotope shift (IS) of H-like Ne,
$\Delta g = g(^{20}_{10}\mathrm{Ne}^{9+}) - g(^{22}_{10}\mathrm{Ne}^{9+})$:

- Differences of g factors of two similar ions can be measured very **accurately**, since several systematic effects cancel;
- Different isotopes: different number of **neutrons**, sensitivity to such new physics
- Same number of protons: **QED** (“old physics”) largely cancels



Bounds on the coupling strength extracted from the experimental Δg:



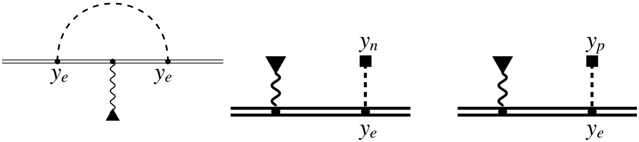
- IS-NL: isotope shift nonlinearity experiments
  Ca^+: J. Berengut *et al.*, Phys. Rev. Lett. **120**, 091801 (2018);
  Yb^+: I. Counts *et al.*, Phys. Rev. Lett. **125**, 123002 (2020)
- H-D: hydrogen-deuterium isotope shift, laser spectroscopy
  C. Delaunay *et al.*, Phys. Rev. D **96**, 115002 (2017)
- $Ar^{15/17+}$: projected possible bound from g factor isotope shift of H-like and Li-like Ar

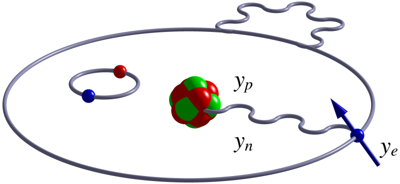
T. Sailer, V. Debierre, Z. H., F. Heiße, C. König, J. Morgner, B. Tu, A. V. Volotka, C. H. Keitel, K. Blaum, S. Sturm, Nature **606**, 479 (2022)

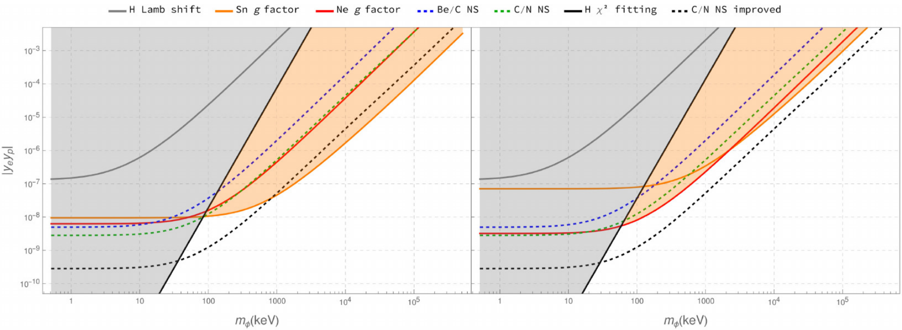
How to constrain the **protonic** coupling?

A highly charged ion contains all fermions: at least one electron, protons and neutrons. Total shift of g factor:

$$\Delta g = \underbrace{\Delta g_{ee}}_{\sim y_e^2} + \underbrace{\Delta g_{en}}_{\sim y_e y_n} + \underbrace{\Delta g_{ep}}_{\sim y_e y_p}$$







- M. Moretti, C. H. Keitel, and Z. H., Phys. Rev. Lett. **136**, 011803 (2026)
- Data for the g factor of H-like Ne^{9+}: F. Heisse *et al.*, Phys. Rev. Lett. **131**, 253002 (2023)
- H data from: R. Potvliege; Experiments + QED theory from CODATA

Tests of BSM physics with the hyperfine splitting of highly charged ions

Pseudoscalars (ALPs)

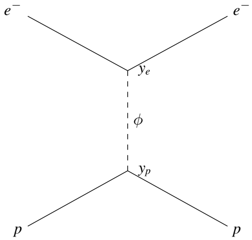
Predicted e.g. in string theory. Often called Axion-Like Particles (ALPs), they arise from spontaneously broken symmetries.

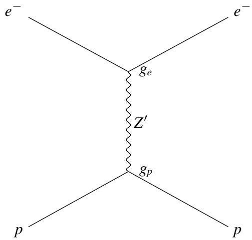
- Spin-dependent couplings
- Potential light dark matter (LDM) candidates

Extra Vector Bosons

One of the simplest BSM extensions involving an additional $U(1)$ gauge factor. Can interact directly or via kinetic mixing.

- Gauge symmetry extensions
- Flavor-dependent interactions

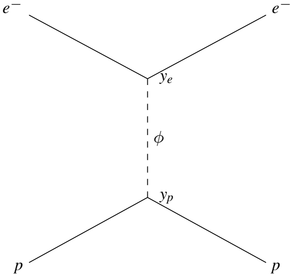


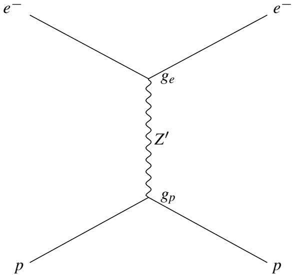


Potentials induced by boson exchange

Yukawa-type potentials[1]**:**

$$
\begin{aligned}
V_{\phi/Z}(r) &= \frac{g_N g_e}{8\pi m_N}\boldsymbol{\mu}_N \cdot \boldsymbol{T}\,\frac{e^{-m_{\phi/Z} r}}{r}(m_{\phi/Z} + 1/r), \\
\boldsymbol{T} &= \begin{cases} i\hat{\boldsymbol{r}}\gamma^0\gamma^5, & \text{pseudoscalar,} \\ \hat{\boldsymbol{r}} \times \gamma^0\boldsymbol{\gamma}, & \text{vector} \end{cases}
\end{aligned}
\tag{2}
$$





[1] P. Fadeev, Y. V. Stadnik, F. Ficek, M. G. Kozlov, V. V. Flambaum, and D. Budker, Phys. Rev. A 99, 022113 (2019); V. A. Dzuba, V. V. Flambaum, I. B. Samsonov, and Y. V. Stadnik, Phys. Rev. D **98**, 035048 (2018)

The normalized/specific difference method

Suppressing nuclear structure effects:

$$\Delta' E = \Delta E_{\text{Li-like}} - \xi \Delta E_{\text{H-like}}$$

Mitigating the Bohr-Weisskopf (BW) Effect:

- Finite nuclear size and magnetization distribution (BW effect) errors limit theoretical precision
- The scaling factor ξ is calculated as the ratio of BW shifts between the Li-like and H-like ground states[2]
- This weighted difference effectively cancels out the dominant nuclear modeling uncertainties

[2] S. G. Karshenboim and V. G. Ivanov, Phys. Lett. B **524**, 259 (2002); V. M. Shabaev, A. N. Artemyev, V. A. Yerokhin, O. M. Zherebtsov, and G. Soff, Phys. Rev. Lett. **86**, 3959 (2001)

Overview of experimental and QED theory inputs

Element	Spin (I)	Theory (meV)	Experiment (meV)	Ref.
^{1}H	$1/2$	$2.02458(10) \times 10^{-7}$	$2.02479(28) \times 10^{-7}$	[3]
^{3}He^{+}	$1/2$	$-4.9218(6) \times 10^{-6}$	$-4.92136(29) \times 10^{-6}$	[4]
^{9}Be	$3/2$	$-1.224(15) \times 10^{-6}$	$-1.1358(5) \times 10^{-6}$	[5]
^{209}Bi	$9/2$	$-61.043(35)$	$-61.012(26)$	[6]

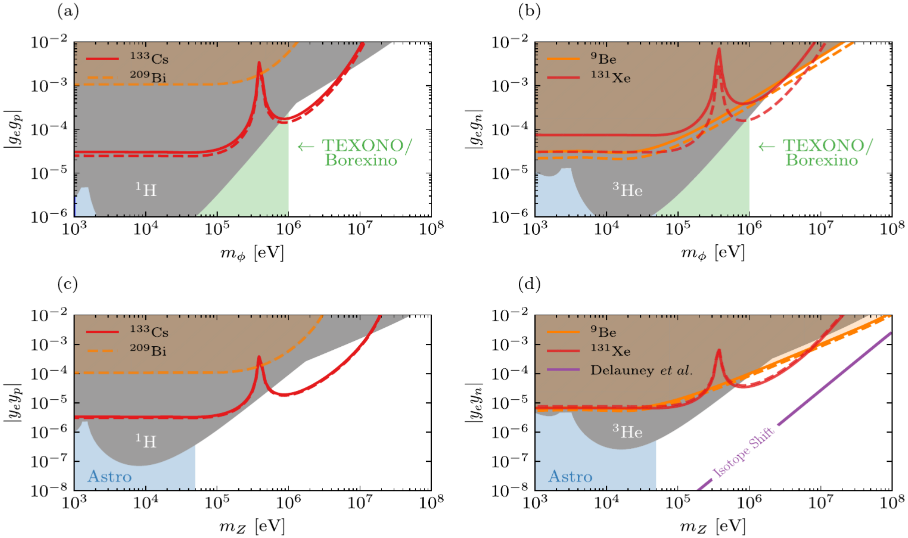
[3] L. Cong, F. Ficek, P. Fadeev, and D. Budker, Phys. Rev. A **112**, 052824 (2025)

[4] S. G. Karshenboim, Phys. Rep. **422**, 1 (2005)

[5] S. Dickopf, B. Sikora, A. Kaiser *et al.*, Nature **632**, 757 (2024); M. Puchalski, K. Pachucki, Phys. Rev. A **89**, 032510 (2014)

[6] J. Ullmann *et al.*, Nat. Commun. **8**, 15484 (2017); V. M. Shabaev, A. N. Artemyev, V. A. Yerokhin *et al.*, Phys. Rev. Lett. **86**, 3959 (2001)

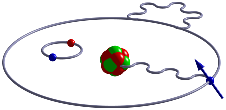
Bounds from existing (Bi) and projected (Cs) experiments:

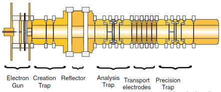


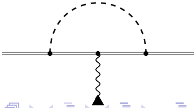
- C. Quint, F. Heiße, J. Jaeckel, L. Leimenstoll, C. H. Keitel, and Z. H., Phys. Rev. Lett. **136**, 113001 (2026)

Summary

- Accurate **test of QED** in strong fields with the g factor of highly charged ions
- Testing the QED of many-body systems
- Competitive tests of hypothetical **new physics** possible through g-factor experiments with highly charged ions: stringent bounds on the coupling constants of **scalar bosons** in the **high-mass regime**
- Hyperfine splitting measurements: stringent bounds on the coupling constants of **pseudoscalar and vector bosons** in the **high-mass regime**
- High flexibility: fermion-resolved determination of coupling constants: coupling to **electrons, protons, neutrons** – not all possible with other methods (e.g. isotope shift experiments with optical clocks)







Bedankt voor uw andacht!
感谢聆听，欢迎提问！
Dziękuję za uwagę!
Grazie per l’attenzione!
İlginiz için teşekkürler!
ध्यान देने के लिए आपका धन्यवाद।
Köszönöm a figyelmet!
Merci à tous pour votre attention !
Muchas gracias por su atención!
Mulţumesc pentru atenţie!
Obrigado pela atenção!
Спасибо за внимание!
Thank you for your attention!
Vielen Dank für Ihre Aufmerksamkeit!

Collaboration

- **Theory, MPIK:**
  B. Sikora, V. A. Yerokhin, M. Moretti, H. Cakir, V. Debierre, N. S. Oreshkina, C. H. Keitel

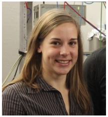
   

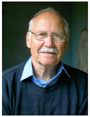
- **Theory, St. Petersburg, Russia:**
  I. I. Tupitsyn

- **Theory, Warsaw and Poznan, Poland:**
  K. Pachucki, M. Puchalski

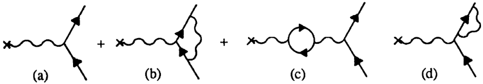
- **Theory, MPQ/LMU München/Pulkovo:**
  S. Karshenboim
- **Penning trap experiments, MPIK/Mainz University/GSI:**
  S. Sturm, F. Heisse, F. Köhler-Langes, A. Kracke (Wagner), G. Werth, W. Quint, K. Blaum, *et al.*

The g factor of the free electron

Interaction energy of an electron with an external **magnetic field**

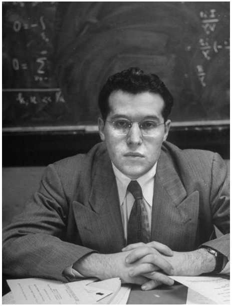


At the one-loop level, it is only corrected by the vertex diagram

$$\Delta E = -\langle \vec{\mu} \rangle \cdot \vec{B} \, ,$$

with the magnetic moment μ, the Bohr magneton $\mu_B = \frac{e\hbar}{2mc}$

$$\langle \vec{\mu} \rangle = g \mu_B \langle \vec{S} \rangle \, .$$

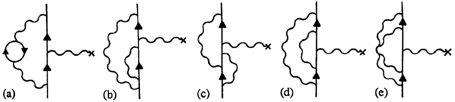


Thus the **g-factor of the free electron up to the one-loop order** is

$$g_{\text{free}} = 2 + \frac{\alpha}{\pi} \approx 2(1 + 0.00116141)$$

The α/π term is the Schwinger term (Schwinger, 1947)

Two-loop diagrams:



A. Peterman, Helv. Phys. Act **30**, 407 (1957);
C. M. Sommerfield, Ann. Phys. **5**, 26 (1958)

Three$^+$-loop diagrams:

S. Laporta, E. Remiddi, Phys. Lett. B **379**, 283 (1996) [3 loops, analytical]
T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, Phys. Rev. Lett. **109**, 111807 (2012) [numerical]
S. Laporta, Phys. Lett. B **772**, 232 (2017) [4 loops, semi-analytical, 1100 digits given]

Current best experimental value:

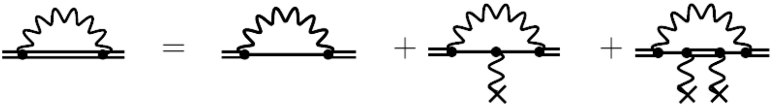
$$g_{\rm exp} = 2.002\,319\,304\,361(6)$$

(rel. accuracy=$3 \cdot 10^{-12}$)
Accurate value for the **fine-structure constant**: $g_{\rm exp}$ and corresponding multi-loop free-electron QED calculations

D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008)

QED theory of the bound-electron g factor

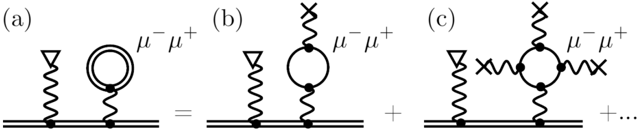
Bound-state QED in the Furry picture:
relate the diagrams to (known) free QED



self-energy function $\Sigma(p)$ momentum space

vertex function $\Gamma_\mu(p,p')$ momentum space

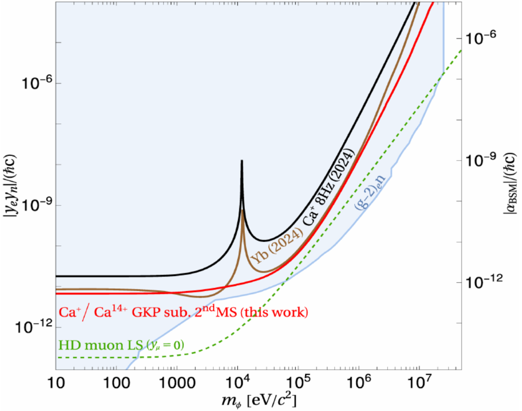
Coulomb-Dirac propagator $G^{2+}(\mathbf{x},\mathbf{y},E)$ coordinate space



free-loop approximation polarization function $\Pi(q^2)$ $\rightarrow$ Uehling potential $V_\mathrm{U}(r)$

virtual light-by-light scattering

Very recent results from King plot nonlinearity



- C^{14+} and C^+ ions: A. Wilzewski *et al.*, Phys. Rev. Lett. **134**, 233002 (2025)
  Experiments: groups of Piet O. Schmidt, Klaus Blaum (PENTATRAP), José Crespo (EBIT)
- Yb^+ ions: M. Door, C. Yeh, M. Heinz *et al.*, Phys. Rev. Lett. **134**, 063002 (2025)
  Experiments: group of T. E. Mehlstäubler, Klaus Blaum (PENTATRAP)