Scale Separation in Exotic Atoms

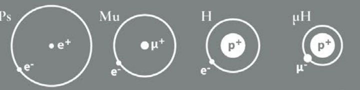
Precision Spectroscopy as Window to New Physics

Sotiris Pitelis

Institut für Kernphysik,
Johannes Gutenberg-Universität Mainz

Separation of Scales across Hydrogen-like Atoms

The **Bohr radii** of hydrogen-like atoms vary based on the **reduced mass** of the atom:



Bohr radii separated by ~3 ORDERS OF MAGNITUDE

This leads to **significant differences** in their atomic spectra:

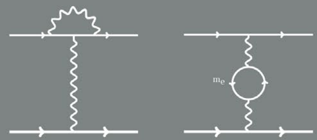


FIG 1: Leading contributions to the H (left) and μH (right) Lamb Shift.

Finite-Size Contribution: To Expand or Not?

- Finite-size contribution to the 2P-2S Lamb shift in (muonic-) hydrogen due to the proton electric Sachs form factor $G_E(Q^2)$:

$$E_{\mathrm{LS}}^{\mathrm{fin.}} = -\frac{(Z\alpha)^4 m_r^3}{2\pi}\int_{t_0}^{\infty} \mathrm{d}t \frac{\mathrm{Im}\, G_E(t)}{(\sqrt{t}+Z\alpha m_r)^4}$$

m_r is the reduced mass of the proton-lepton system, $Q^2 = -q^2$ is the squared momentum transfer, and t_0 is the lowest particle-production threshold in the t-channel.

- Finite-size expansion:

$$E_{\mathrm{LS}}^{\mathrm{fin.}} \simeq -\frac{(Z\alpha)^4 m_r^3}{12}\left[\langle r^2\rangle_E - Z\alpha m_r \langle r^3\rangle_E\right] + O(\alpha^6)$$

where $\langle r^2\rangle_E$ and $\langle r^3\rangle_E$ are the second and third moments of the proton charge distribution.

- Breaks down when $\sqrt{t_0}$ becomes comparable to $Z\alpha m_r$, which is the inverse Bohr radius of the system.

TABLE I: Inverse Bohr radii of hydrogen-like atoms

SYSTEM	Ps	Mu	H	μH
$Z\alpha m_r$ [MeV]	1.86×10^{-3}	3.71×10^{-3}	3.73×10^{-3}	0.693

How does this affect our calculations?

Enhanced Soft Contributions in the Standard Model

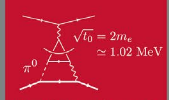


FIG 2: Soft SM contribution to the proton form factor which breaks the finite-size expansion

- Soft contributions can break the finite-size expansion: see f.i. the **light particle cut** across the upper loop of the diagram in FIG 2.
- Breaking occurs in systems with $Z\alpha m_r \sim 2m_e$, like μH.
- Not a problem with current experimental accuracy, but...

In hydrogen-like atoms, light cuts may be enhanced depending on the lightest t-channel cut compared to the Bohr radius of the atom!

TABLE II: Breaking of the expansion in moments of charge distribution for the 2-loop diagram in FIG 2

SYSTEM	EXACT CALCULATION	EXPANSION	CURRENT EXPERIMENTAL ACCURACY
H [kHz]	-3.65×10^{-11}	-1.33×10^{-11}	3.2
μH [μeV]	-7.82×10^{-10}	-1.14×10^{-7}	2.3

New Physics Searches: Picking the Right Tool for the Job

- Different atoms are sensitive to different ranges of New Physics parameters, such as the masses and couplings of BSM particles.
- Theoretical studies show the sensitivity of various systems to different BSM scenarios.
- Consider the BSM scenario in FIG 3, with a light cut to due to the production of a light DM fermion pair.

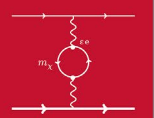


FIG 3: Potential BSM contribution to the Lamb shift through a Dark Matter fermion

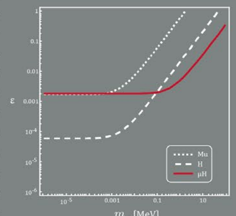


FIG 4: Sensitivity plot for the BSM scenario of FIG 3, indicating when the size of the contribution reaches the present experimental accuracy for the individual atoms

- State-of-the-art results for the Lamb shift:

  Mu: 4.3309(105) μeV
  H: 4.37483(1) μeV
  μH: 202.3706(23) meV

- μH is less accurately measured than Mu, but **equally or more sensitive** due to its smaller Bohr radius.
- H is measured most accurately (5 orders of magnitude better than μH), but μH is still more sensitive at higher m_χ!

When using hydrogen-like atoms as labs for New Physics searches, we can use the range of their Bohr radii to our advantage!

Light New Physics?

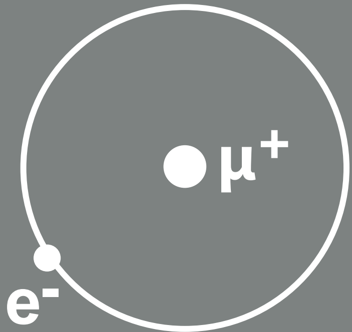
Discuss!

This work is supported by the Deutsche Forschungsgemeinschaft through the Emmy Noether Programme (grant 449369623)

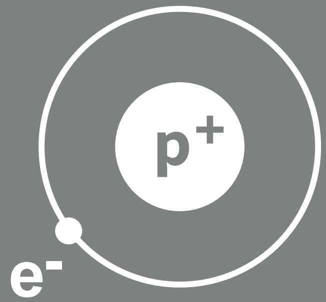
JG|U
Johannes Gutenberg Universität Mainz

Emmy Noether-Programm

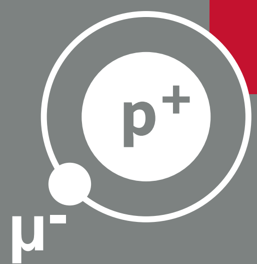
DFG Deutsche Forschungsgemeinschaft



Scale Separation in Exotic Atoms



Sotiris Pitelis
in collaboration with F. Hagelstein,
V. Lensky and V. Pascalutsa



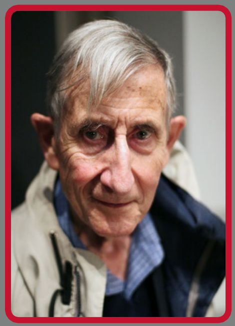
EINN 2023

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

02.11.23

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Frontiers of New Physics Searches



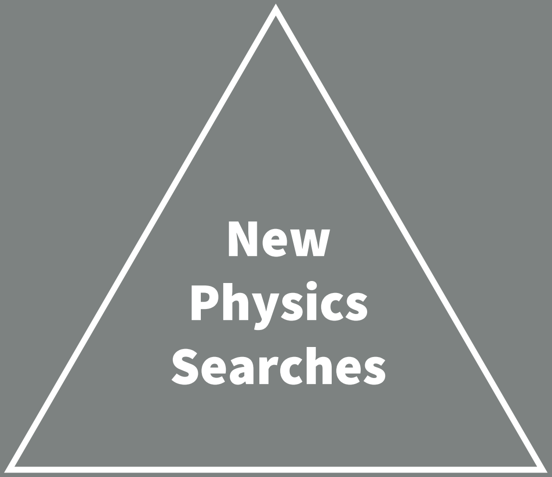
Freeman Dyson

"If you look for nature's secrets in only one direction, you are likely to miss the most important secrets..."

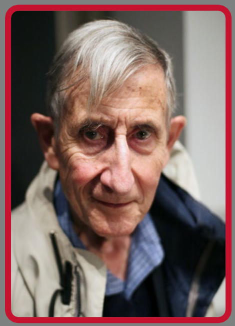
Frontiers of New Physics Searches

Freeman Dyson

"If you look for nature's secrets in only one direction, you are likely to miss the most important secrets..."

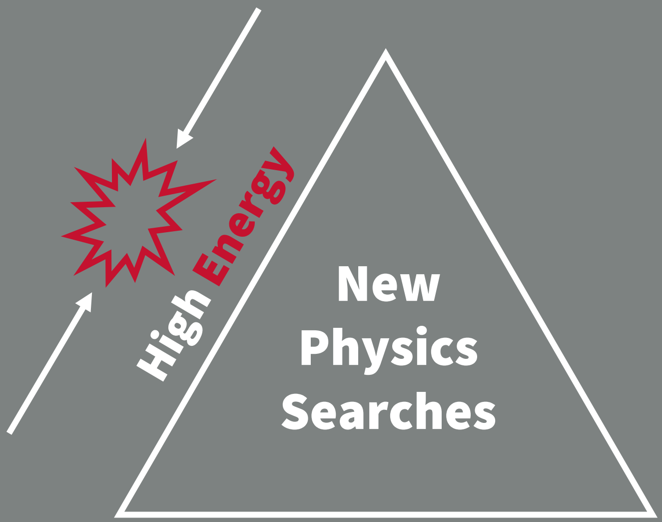


Frontiers of New Physics Searches



Freeman Dyson

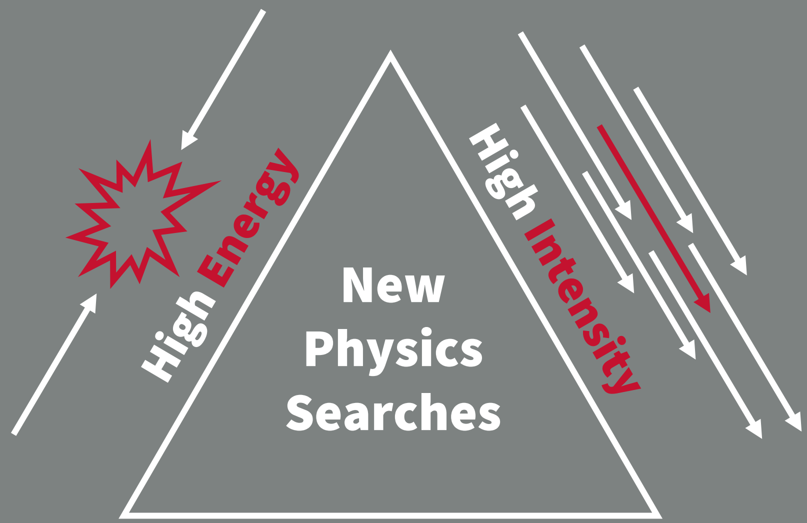
"If you look for nature's secrets in only one direction, you are likely to miss the most important secrets..."



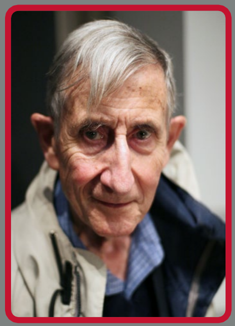
Frontiers of New Physics Searches

Freeman Dyson

"If you look for nature's secrets in only one direction, you are likely to miss the most important secrets..."

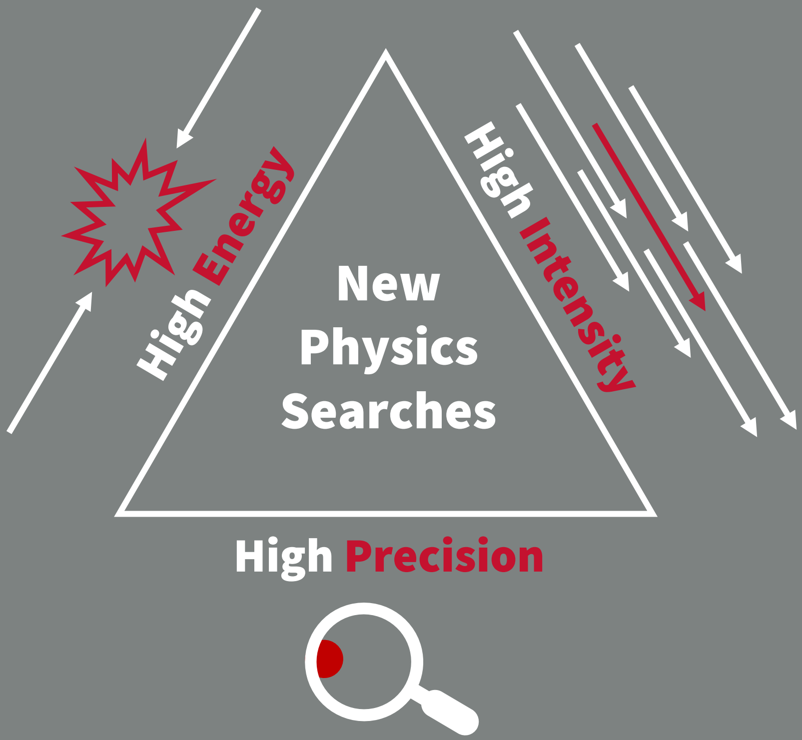


Frontiers of New Physics Searches

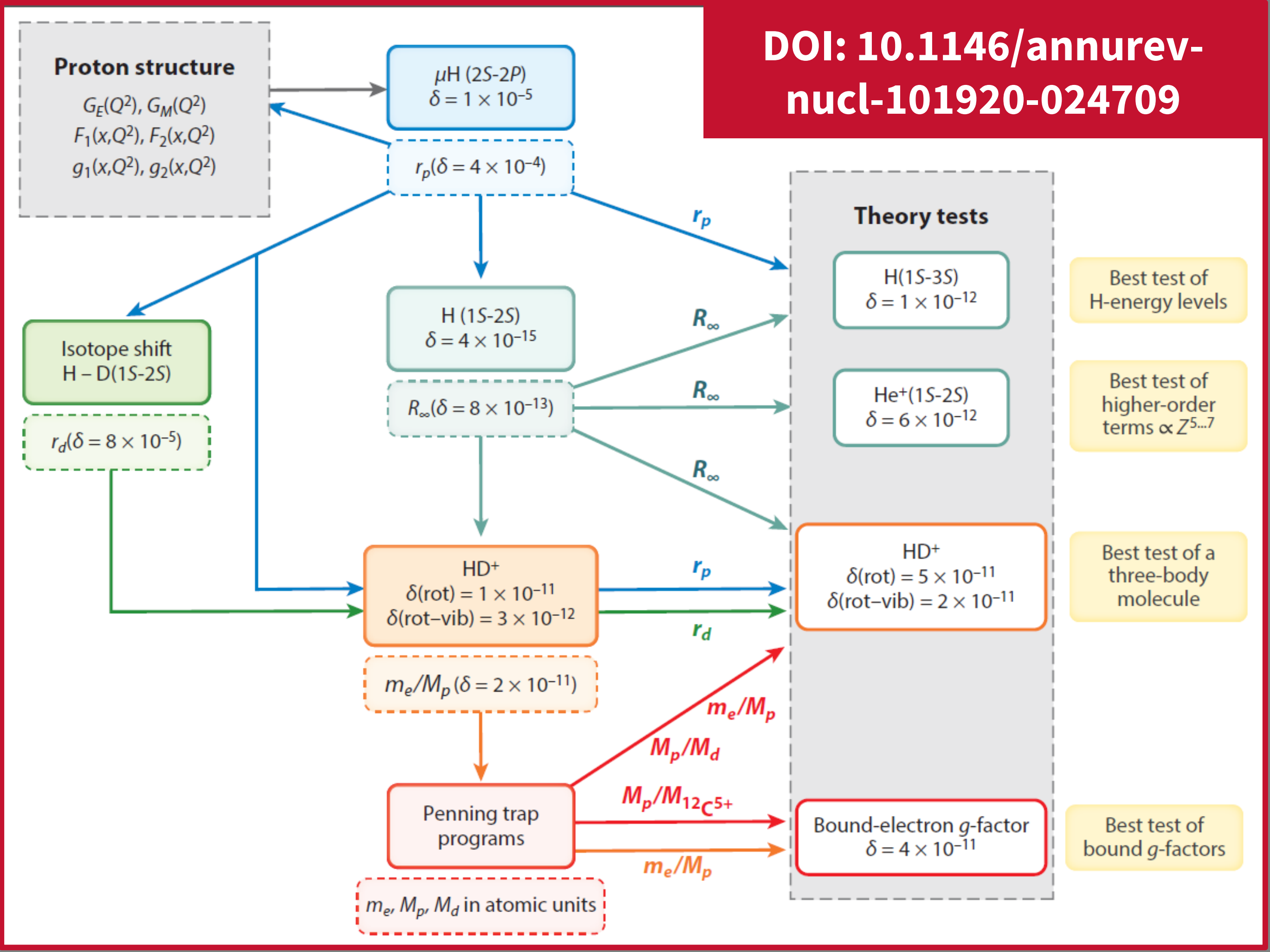


Freeman Dyson

"If you look for nature's secrets in only one direction, you are likely to miss the most important secrets..."

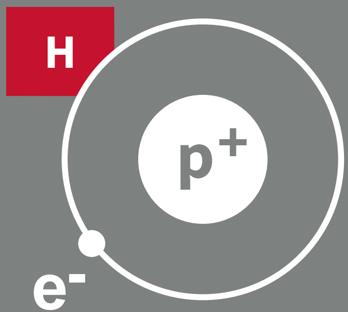


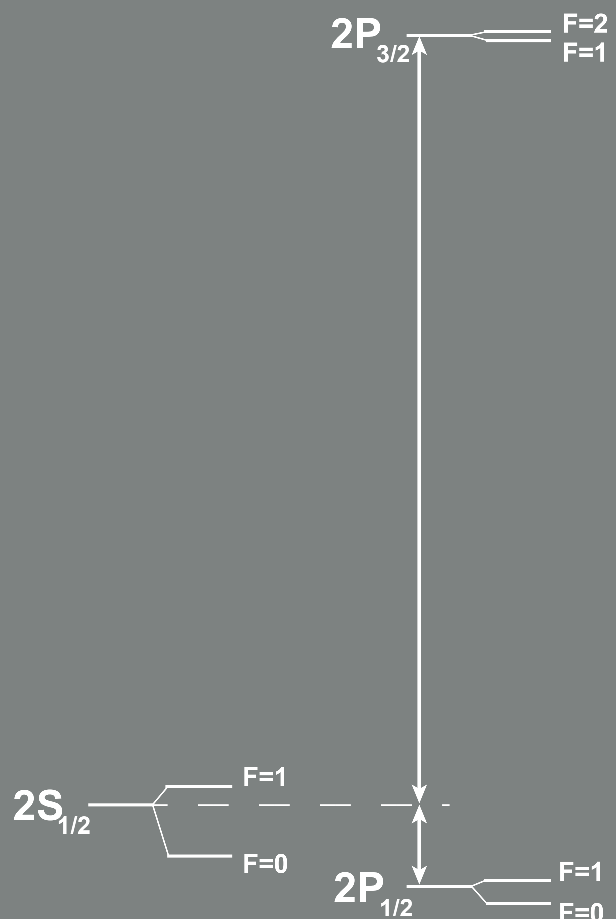
The Precision Frontier



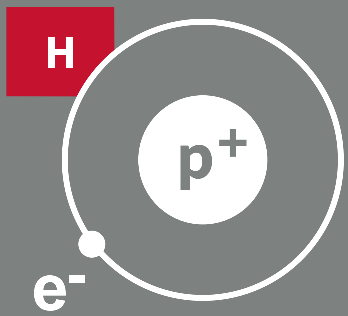
DOI: 10.1146/annurev-nucl-101920-024709

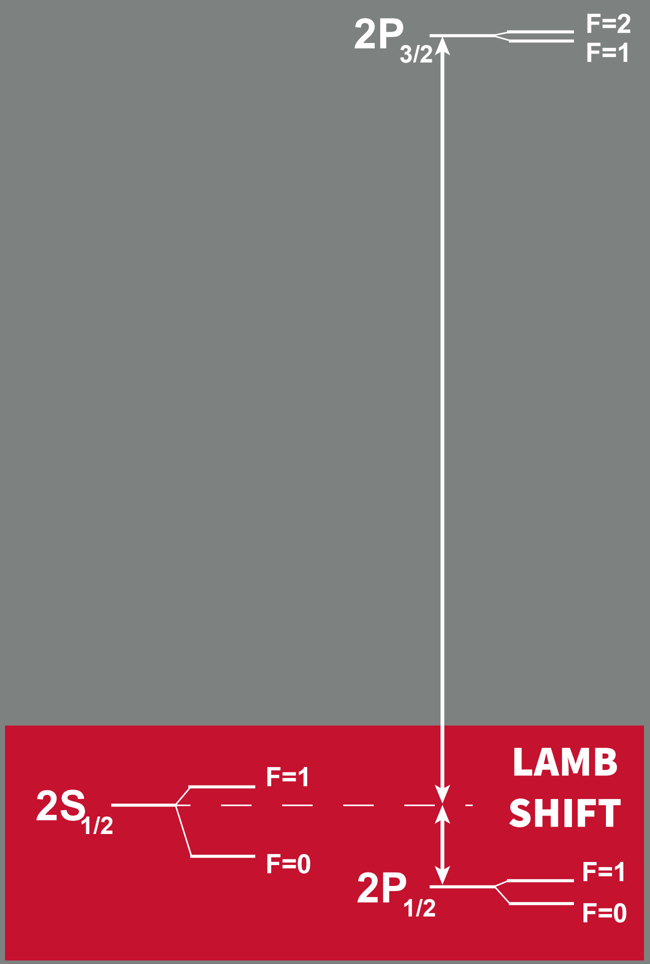
Precision Atomic Spectroscopy



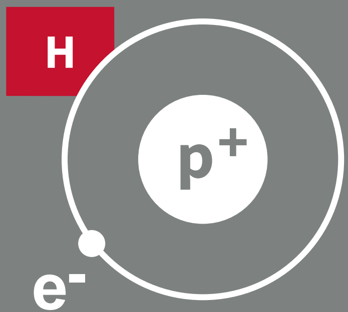


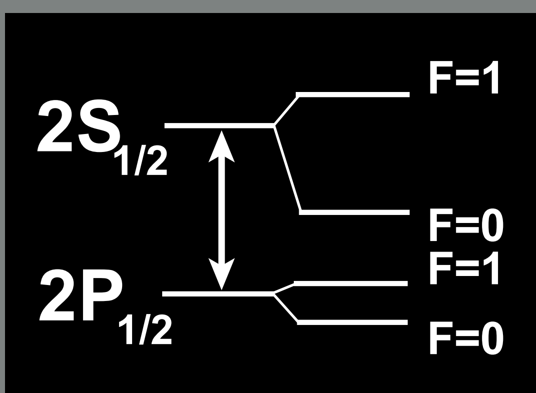
Precision Atomic Spectroscopy



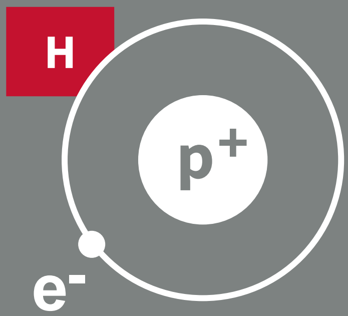


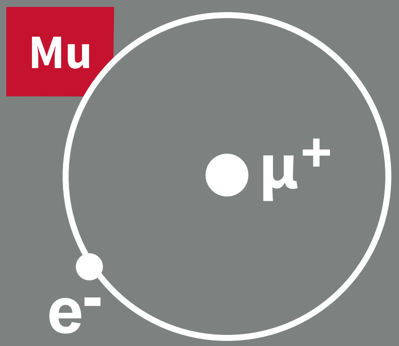
Precision Atomic Spectroscopy

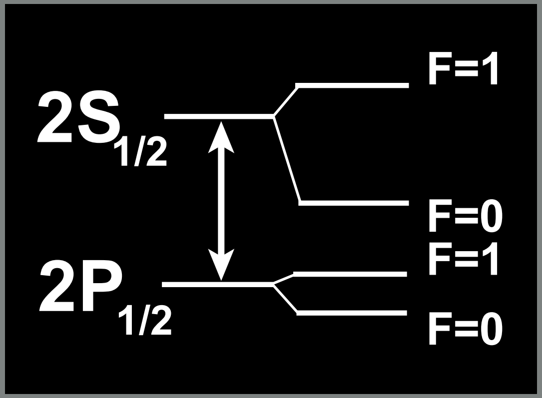




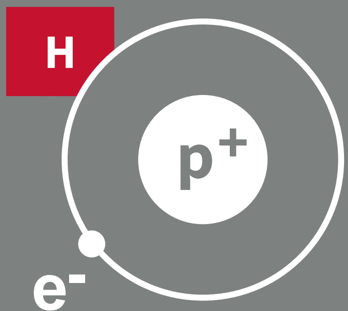
Precision Atomic Spectroscopy

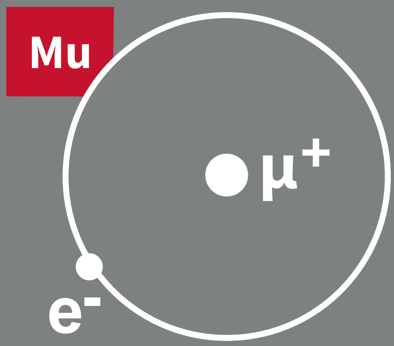


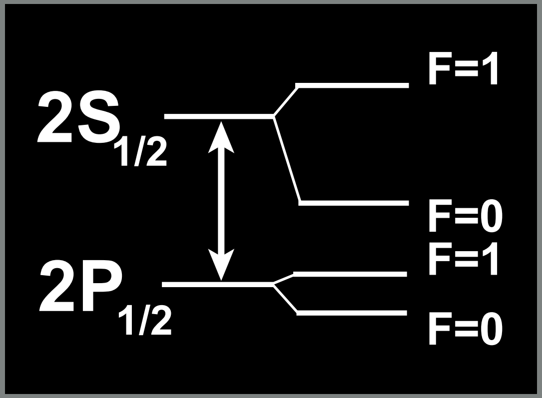


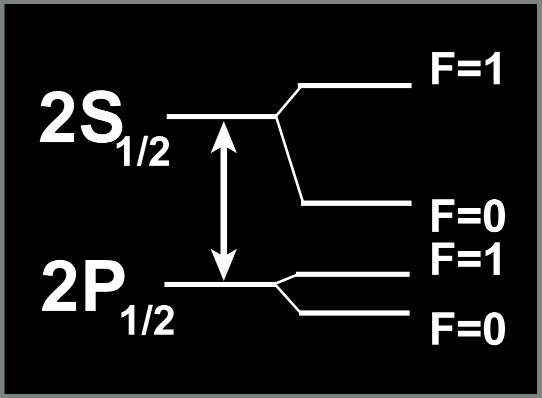


Precision Atomic Spectroscopy

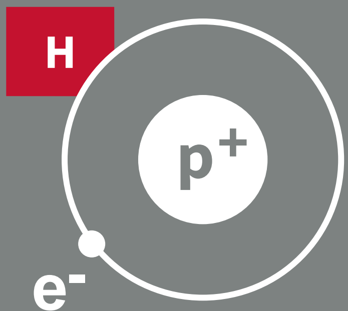


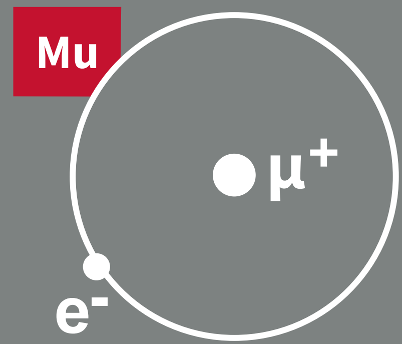


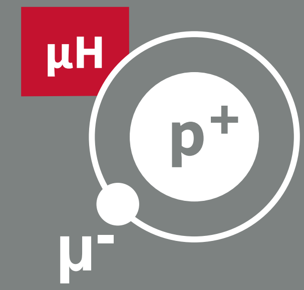


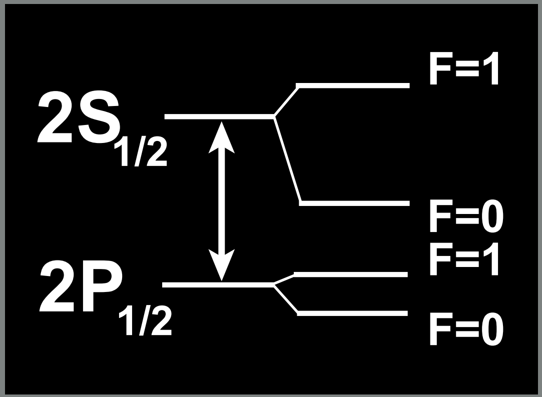


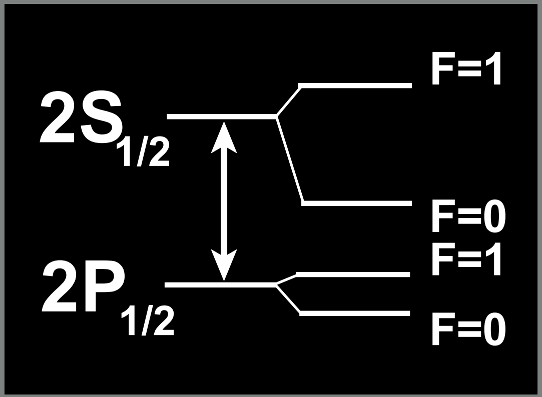
Precision Atomic Spectroscopy



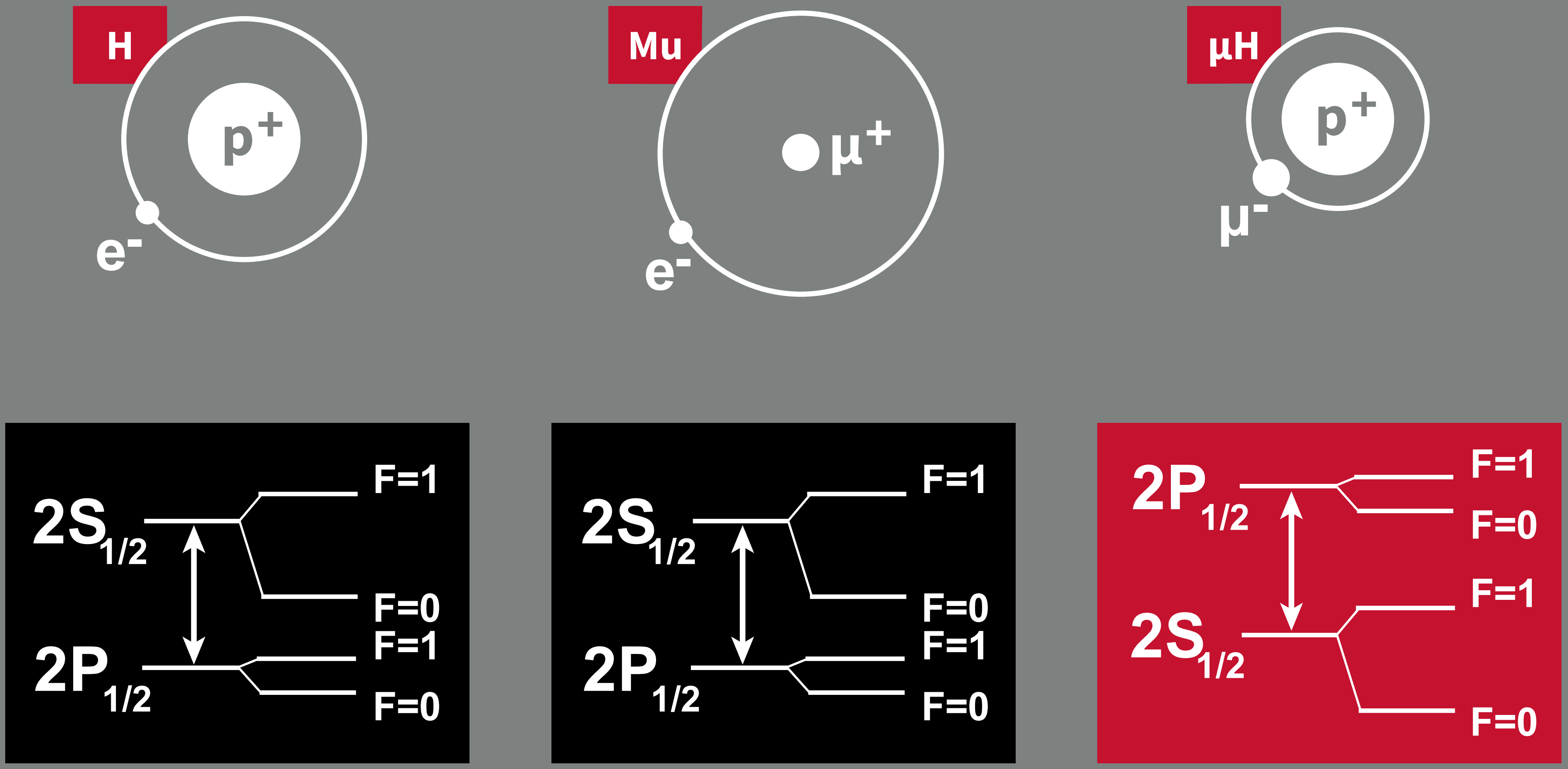




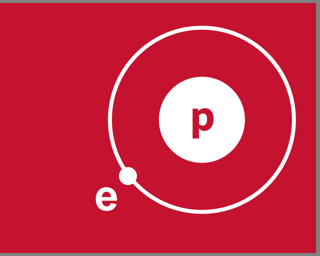


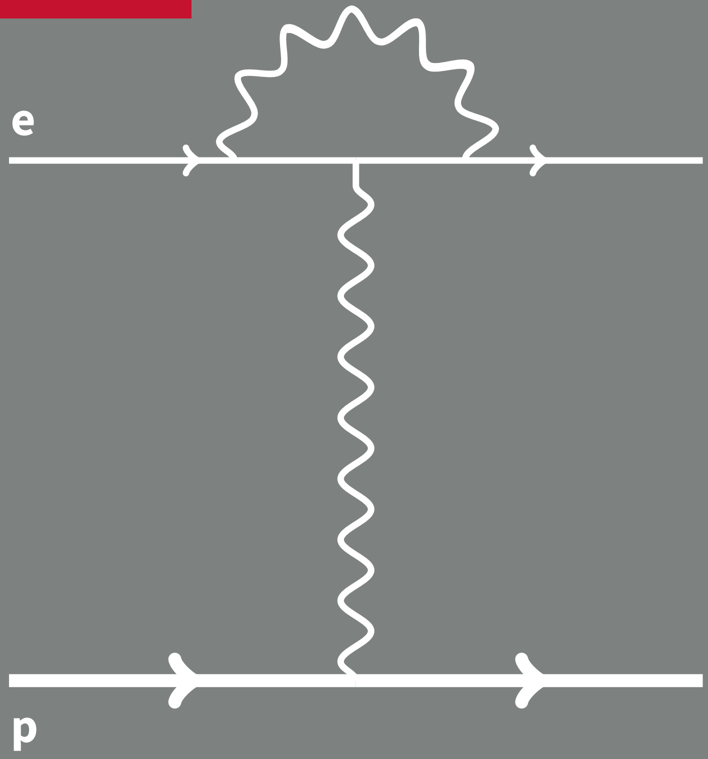


Precision Atomic Spectroscopy

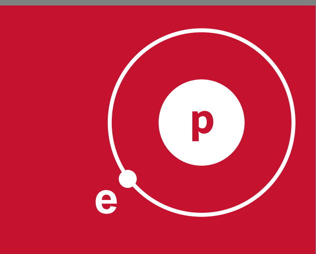


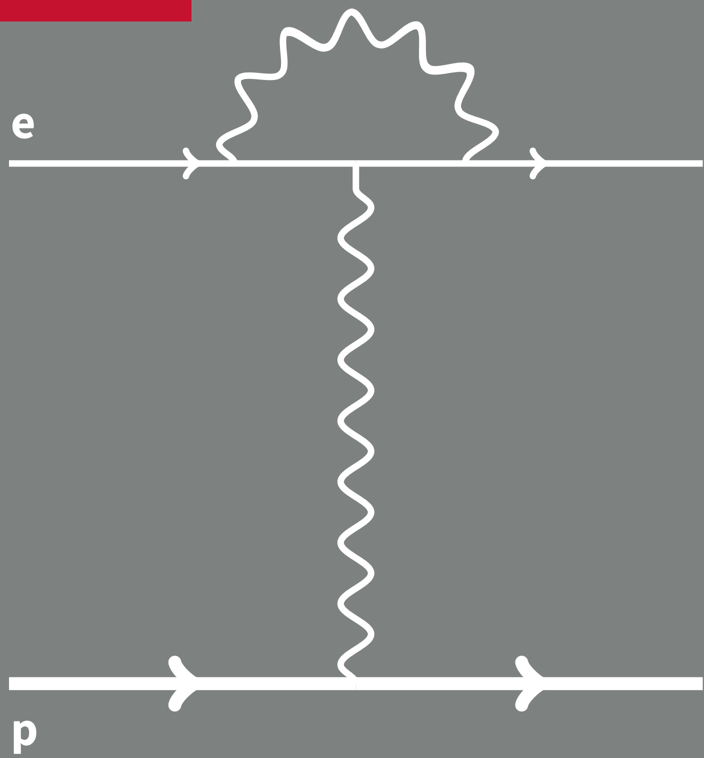
Leading QED Corrections

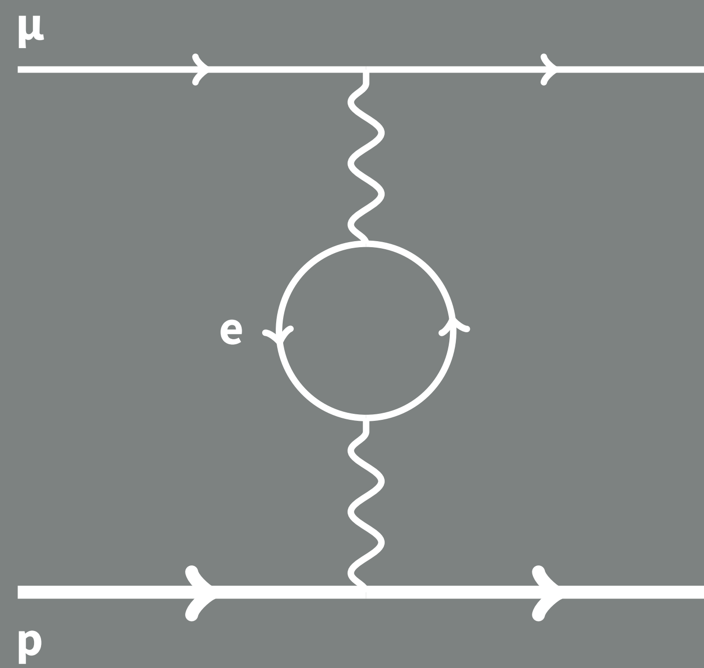




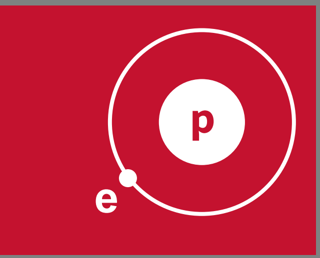
Leading QED Corrections

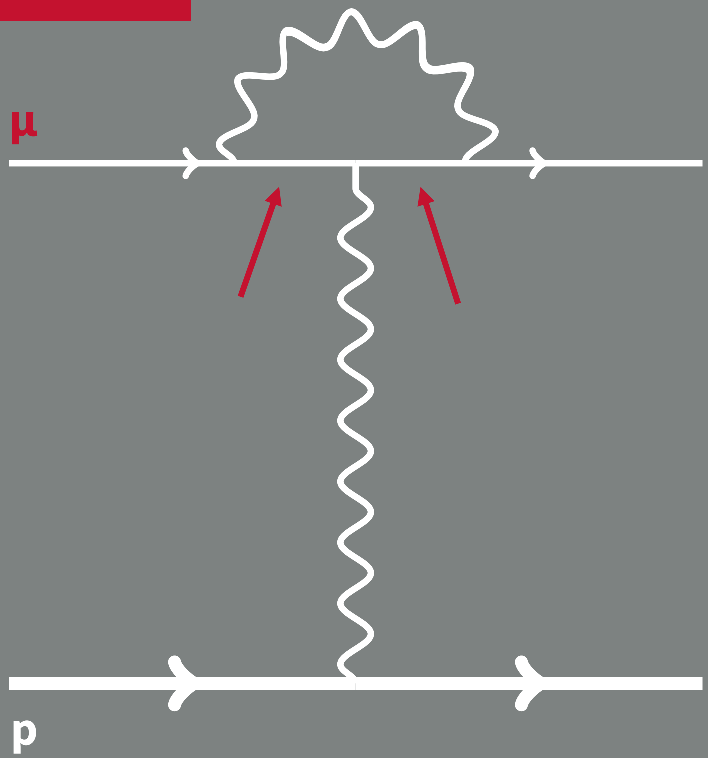


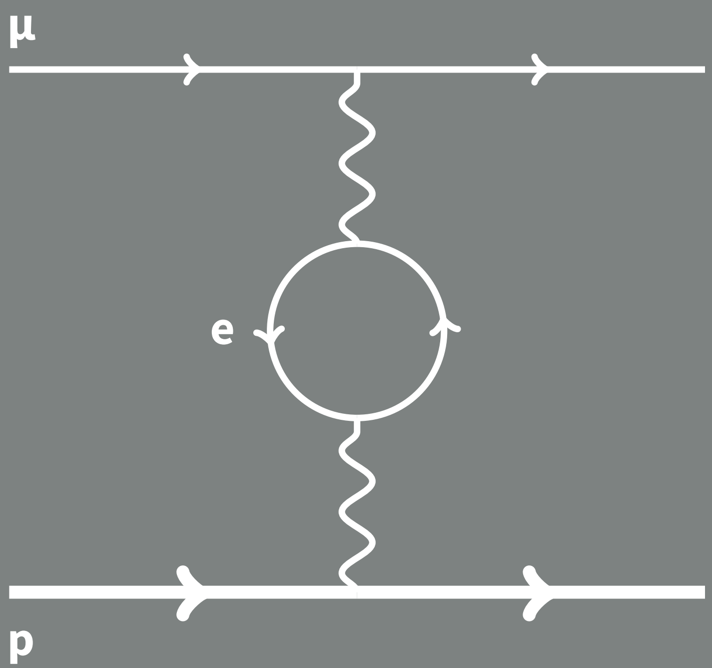




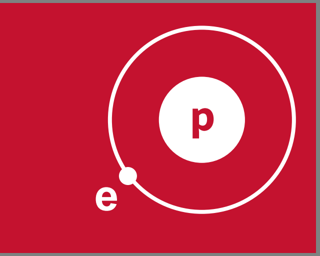
Leading QED Corrections

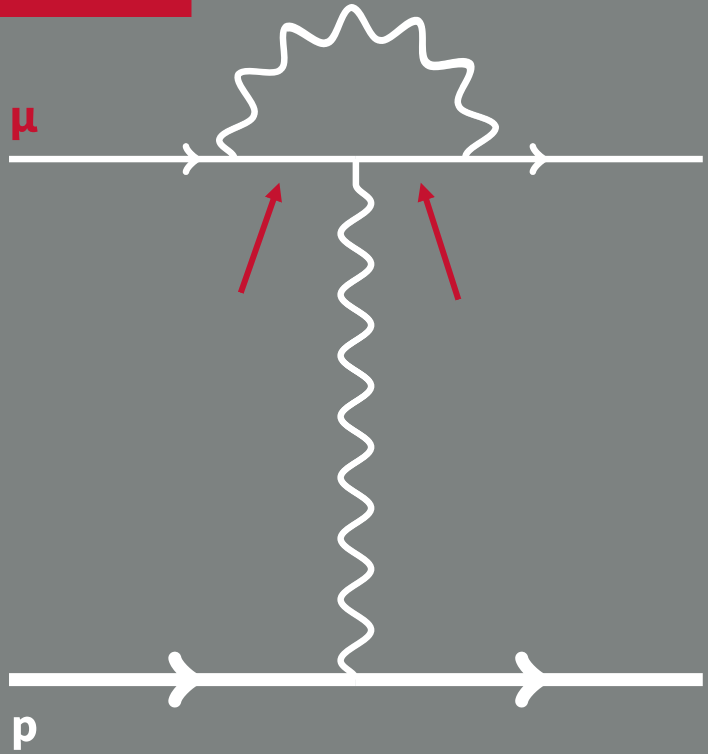


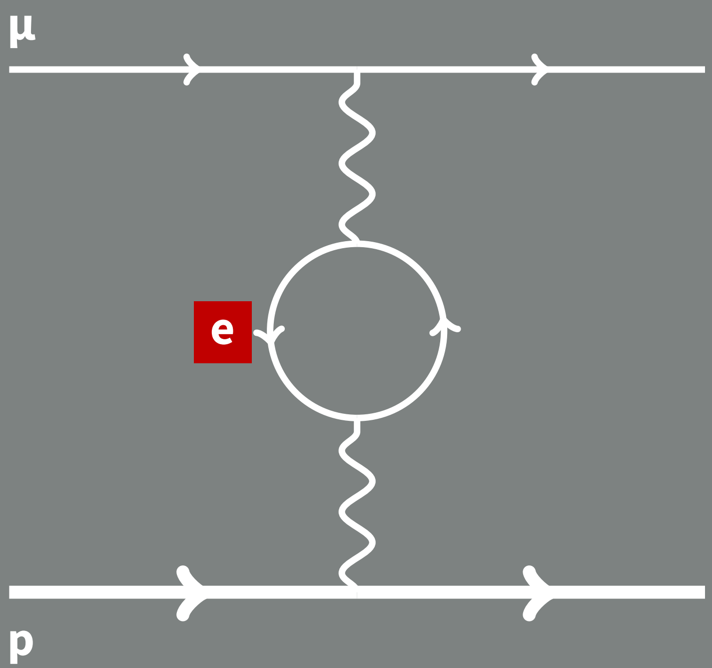




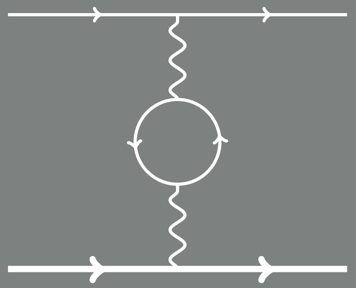
Leading QED Corrections







Electronic Vacuum Polarization in μH

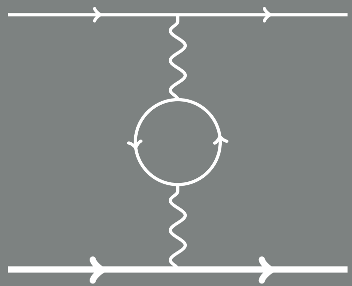


arXiv:2212.13782

Sec.	Order	Correction	μH
III.A	$\alpha\,(Z\,\alpha)^2$	eVP$^{(1)}$	205.007 38
III.A	$\alpha^2\,(Z\,\alpha)^2$	eVP$^{(2)}$	1.658 85
III.A	$\alpha^3\,(Z\,\alpha)^2$	eVP$^{(3)}$	0.007 52
III.B	$(Z, Z^2, Z^3)\,\alpha^5$	light by light eVP	−0.000 89(2)
III.C	$(Z\,\alpha)^4$	recoil	0.057 47
III.D	$\alpha\,(Z\,\alpha)^4$	relativistic with eVP$^{(1)}$	0.018 76
III.E	$\alpha^2\,(Z\,\alpha)^4$	relativistic with eVP$^{(2)}$	0.000 17

⋮

Electronic Vacuum Polarization in μH



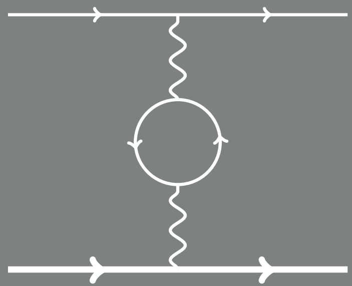
arXiv:2212.13782

Sec.	Order	Correction	μH
III.A	$\alpha\,(Z\,\alpha)^2$	eVP$^{(1)}$	205.007 38
III.A	$\alpha^2\,(Z\,\alpha)^2$	eVP$^{(2)}$	1.658 85
III.A	$\alpha^3\,(Z\,\alpha)^2$	eVP$^{(3)}$	0.007 52
III.B	$(Z, Z^2, Z^3)\,\alpha^5$	light by light eVP	−0.000 89(2)
III.C	$(Z\,\alpha)^4$	recoil	0.057 47
III.D	$\alpha\,(Z\,\alpha)^4$	relativistic with eVP$^{(1)}$	0.018 76
III.E	$\alpha^2\,(Z\,\alpha)^4$	relativistic with eVP$^{(2)}$	0.000 17

⋮

III	E_{QED}	point nucleus	206.034 4(3)

Electronic Vacuum Polarization in μH



arXiv:2212.13782

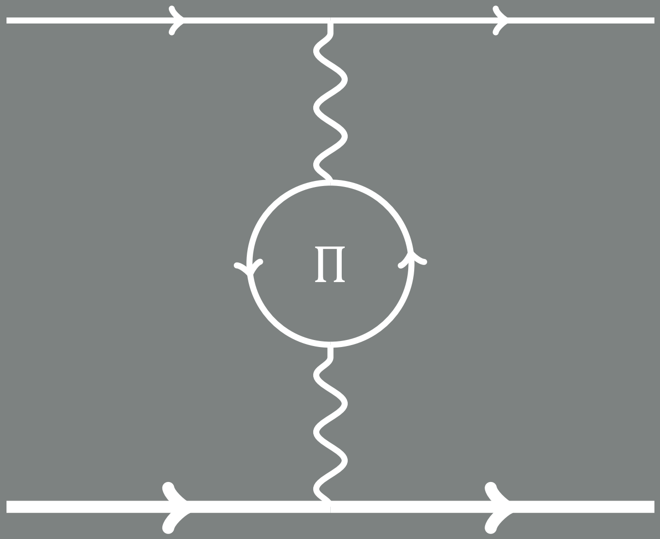
Sec.	Order	Correction	μH
III.A	$\alpha\,(Z\,\alpha)^2$	$\mathrm{eVP}^{(1)}$	205.007 38
III.A	$\alpha^2\,(Z\,\alpha)^2$	$\mathrm{eVP}^{(2)}$	1.658 85
III.A	$\alpha^3\,(Z\,\alpha)^2$	$\mathrm{eVP}^{(3)}$	0.007 52
III.B	$(Z, Z^2, Z^3)\,\alpha^5$	light by light eVP	−0.000 89(2)
III.C	$(Z\,\alpha)^4$	recoil	0.057 47
III.D	$\alpha\,(Z\,\alpha)^4$	relativistic with $\mathrm{eVP}^{(1)}$	0.018 76
III.E	$\alpha^2\,(Z\,\alpha)^4$	relativistic with $\mathrm{eVP}^{(2)}$	0.000 17

⋮

III	E_{QED}	point nucleus	206.034 4(3)

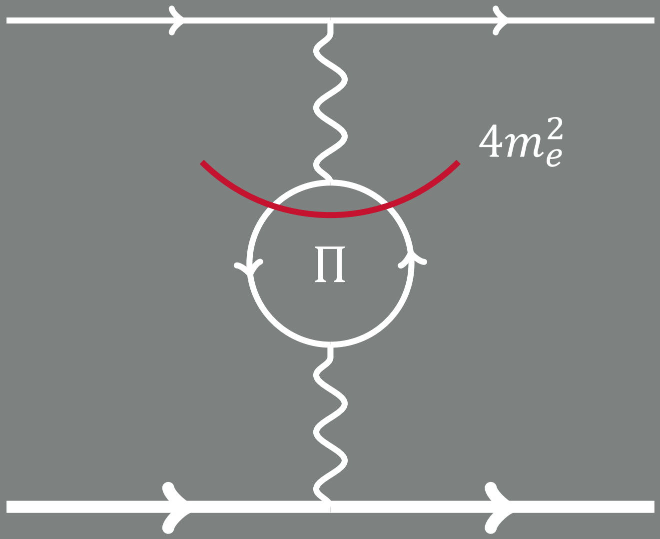
Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \text{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$



Dispersive Calculation of the eVP Contribution

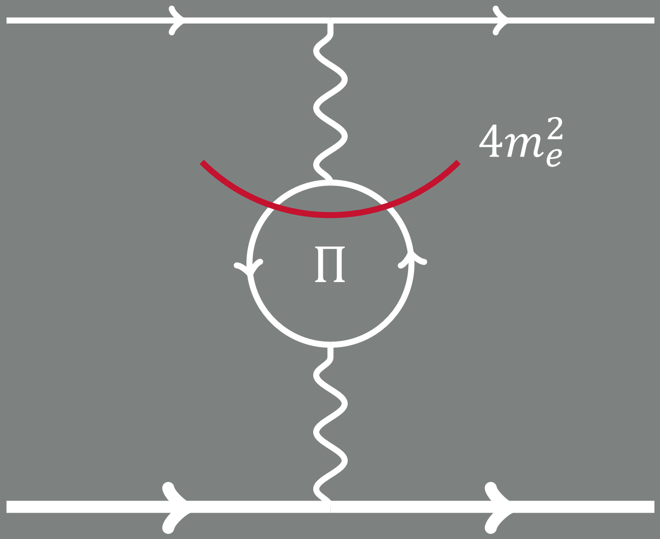
$$E_{2P-2S}^{\langle \text{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$



Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

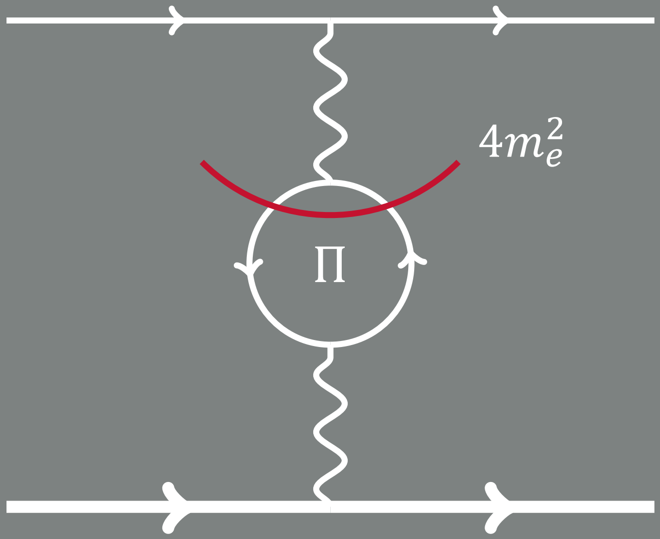
$$= -\frac{\alpha (Z\alpha)^4 m_r^3}{4m_e^2} \frac{1}{2\pi} \int_1^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\Pi(4m_e^2 \, t)}{\left(\sqrt{t} + \frac{m_r}{2 \, m_e} Z\alpha\right)^4}$$



Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \text{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

$$= -\frac{\alpha (Z\alpha)^4 m_r^3}{4m_e^2} \frac{1}{2\pi} \int_{1}^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\Pi(4m_e^2 \, t)}{\left(\sqrt{t} + \frac{m_r}{2\, m_e} Z\alpha\right)^4}$$

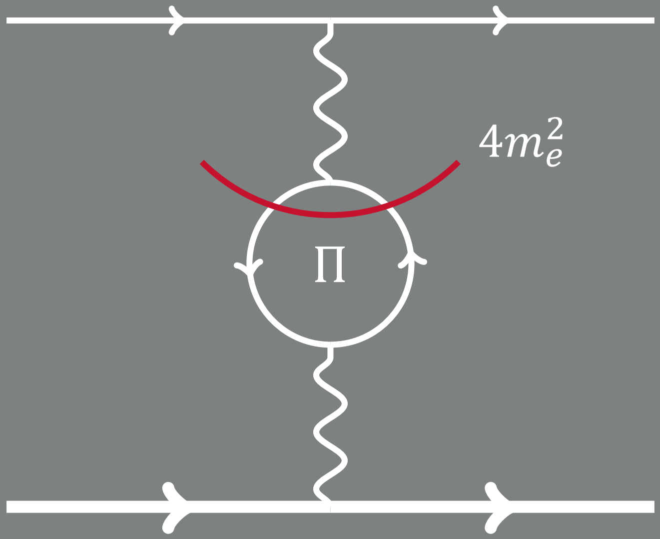


Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

$\alpha(Z\alpha)^2$?

$$= -\frac{\alpha (Z\alpha)^4 m_r^3}{4m_e^2} \frac{1}{2\pi} \int_1^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\Pi(4m_e^2 \, t)}{\left(\sqrt{t} + \frac{m_r}{2\, m_e} Z\alpha\right)^4}$$



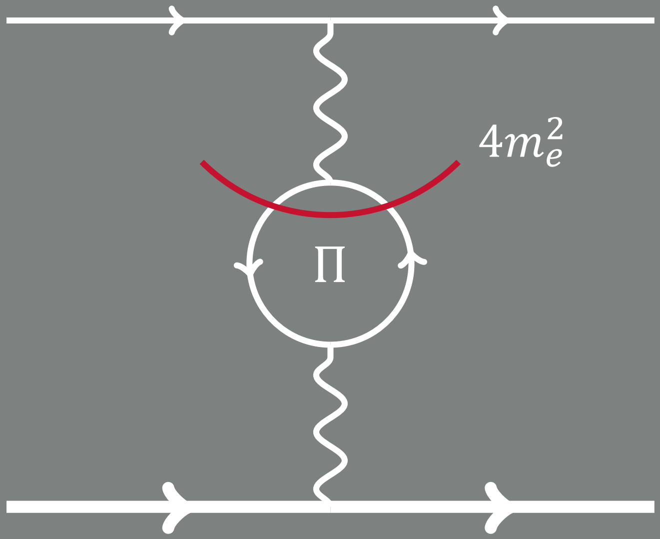
Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

$\alpha (Z\alpha)^2$?

$$= -\frac{\alpha(Z\alpha)^4 m_r^3}{4m_e^2} \frac{1}{2\pi} \int_1^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\Pi(4m_e^2 \, t)}{\left(\sqrt{t} + \frac{m_r}{2\, m_e} Z\alpha\right)^4}$$

$\frac{m_r}{2\, m_e} Z\alpha \rightarrow \kappa$



Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{\alpha \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

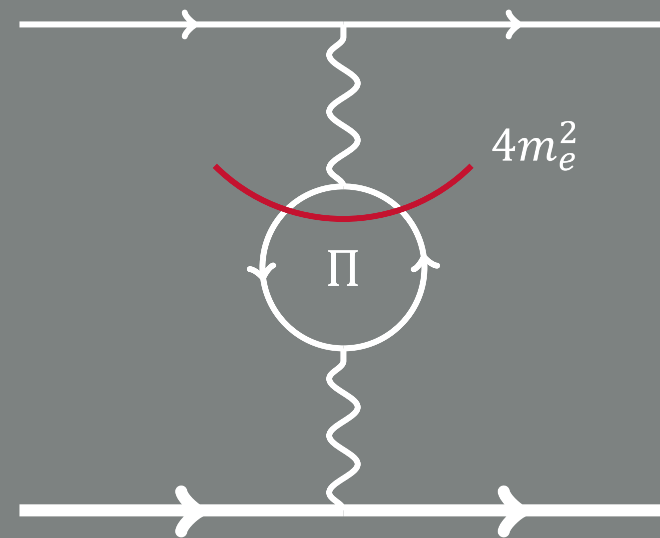
$\alpha(Z\alpha)^2$?

$$= -\frac{\alpha(Z\alpha)^4 m_r^3}{4m_e^2} \frac{1}{2\pi} \int_1^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\Pi(4m_e^2 \, t)}{\left(\sqrt{t} + \frac{m_r}{2\, m_e} Z\alpha\right)^4}$$

$\frac{m_r}{2\, m_e} Z\alpha \rightarrow \kappa$

$$= \alpha(Z\alpha)^2 \kappa^2 m_r$$

$$\times \frac{1}{3\kappa^5} \left(1 + \frac{\kappa(2\kappa^6 - 13\kappa^4 + 44\kappa^2 - 24)}{12\pi(1-\kappa^2)^2} - \frac{15\kappa^4 - 20\kappa^2 + 8}{4\pi(1-\kappa^2)^{\frac{5}{2}}} \mathrm{ArcCos}\, \kappa \right)$$



Dispersive Calculation of the eVP Contribution

$$E_{2P-2S}^{\langle \text{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \text{d}t \, \frac{\alpha \, \text{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

$\alpha(Z\alpha)^2$?

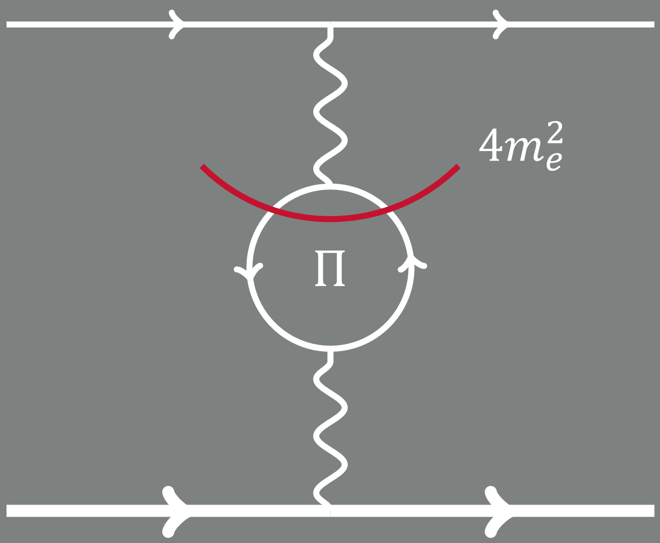
$$= -\frac{\alpha(Z\alpha)^4 m_r^3}{4m_e^2} \frac{1}{2\pi} \int_1^{\infty} \text{d}t \, \frac{\text{Im}\Pi(4m_e^2 \, t)}{\left(\sqrt{t} + \frac{m_r}{2\, m_e} Z\alpha\right)^4}$$

$\frac{m_r}{2\, m_e} Z\alpha \rightarrow \kappa$

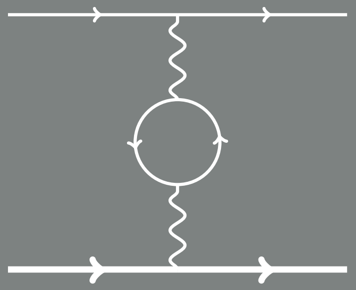
$$= \alpha(Z\alpha)^2 \kappa^2 m_r$$

$$\times \frac{1}{3\kappa^5}\left(1 + \frac{\kappa(2\kappa^6 - 13\kappa^4 + 44\kappa^2 - 24)}{12\pi(1-\kappa^2)^2} - \frac{15\kappa^4 - 20\kappa^2 + 8}{4\pi(1-\kappa^2)^{\frac{5}{2}}} \text{ArcCos}\,\kappa\right)$$

(almost) constant as κ changes

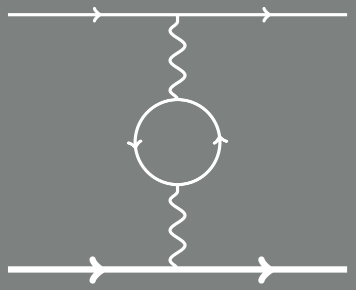


The eVP Contribution Across Different Systems



$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} \propto \alpha (Z\alpha)^2 \kappa^2 m_r, \qquad \kappa = \frac{m_r}{2m_e} Z\alpha$$

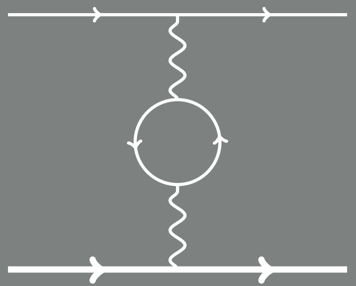
The eVP Contribution Across Different Systems



$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} \propto \alpha (Z\alpha)^2 \kappa^2 m_r, \qquad \kappa = \frac{m_r}{2m_e} Z\alpha$$

System	m_r [MeV]	κ	$\kappa^2 m_r$ [MeV]
Mu	0.509	$0.498\, Z\alpha$	6.71×10^{-6}

The eVP Contribution Across Different Systems

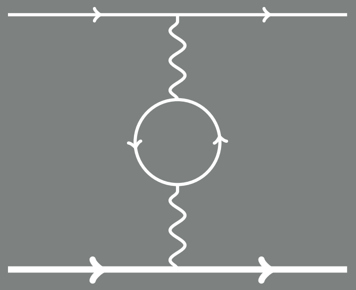


$$E_{2P-2S}^{\langle\text{eVP}\rangle} \propto \alpha(Z\alpha)^2\kappa^2 m_r, \qquad \kappa = \frac{m_r}{2m_e} Z\alpha$$

$$Z\alpha \simeq \frac{1}{137}$$

System	m_r [MeV]	κ	$\kappa^2 m_r$ [MeV]
Mu	0.509	$0.498\, Z\alpha$	6.71×10^{-6}

The eVP Contribution Across Different Systems

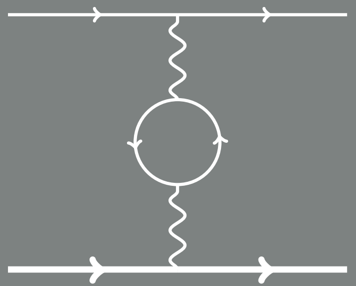


$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} \propto \alpha (Z\alpha)^2 \kappa^2 m_r, \qquad \kappa = \frac{m_r}{2m_e} Z\alpha$$

$$Z\alpha \simeq \frac{1}{137}$$

System	m_r [MeV]	κ	$\kappa^2 m_r$ [MeV]
Mu	0.509	$0.498\, Z\alpha$	6.71×10^{-6}
H	0.511	$0.500\, Z\alpha$	6.79×10^{-6}

The eVP Contribution Across Different Systems

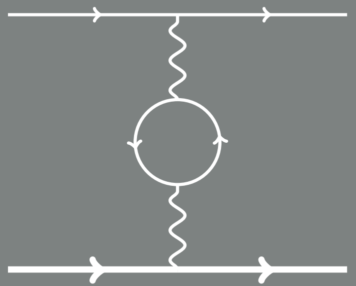


$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} \propto \alpha (Z\alpha)^2 \kappa^2 m_r, \qquad \kappa = \frac{m_r}{2m_e} Z\alpha$$

$$Z\alpha \simeq \frac{1}{137}$$

System	m_r [MeV]	κ	$\kappa^2 m_r$ [MeV]
Mu	0.509	$0.498\,Z\alpha$	6.71×10^{-6}
H	0.511	$0.500\,Z\alpha$	6.79×10^{-6}
μH	94.965	$92.9\,Z\alpha$	43.66

The eVP Contribution Across Different Systems



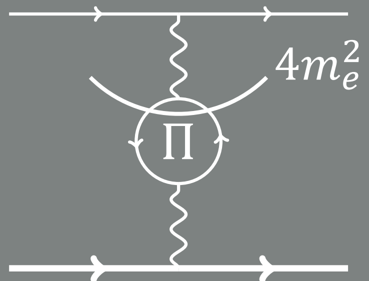
$$E_{2P-2S}^{\langle\mathrm{eVP}\rangle} \propto \alpha(Z\alpha)^2\kappa^2 m_r, \qquad \kappa = \frac{m_r}{2m_e} Z\alpha$$

$$Z\alpha \simeq \frac{1}{137}$$

System	m_r [MeV]	κ	$\kappa^2 m_r$ [MeV]
Mu	0.509	$0.498\, Z\alpha$	6.71×10^{-6}
H	0.511	$0.500\, Z\alpha$	6.79×10^{-6}
μH	94.965	$92.9\, Z\alpha$	43.66

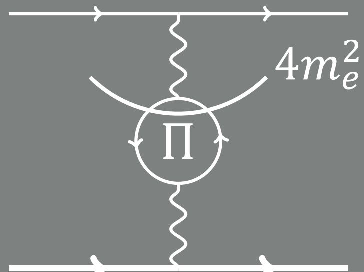
$\alpha\,(Z\,\alpha)^2$ **!**

One-Photon-Exchange Potentials

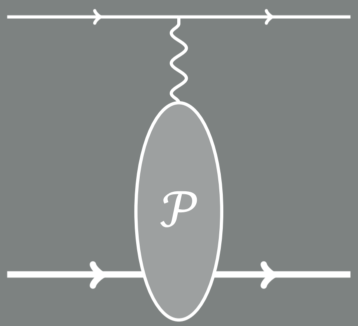


$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{a \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

One-Photon-Exchange Potentials

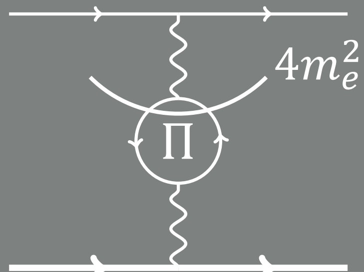


$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{a \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

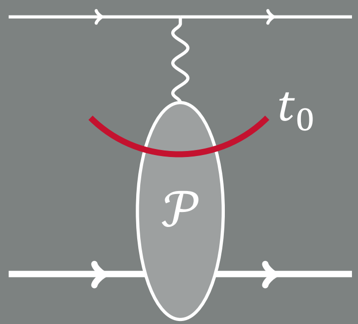


$$E_{2P-2S}^{\langle \mathrm{OPE} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\mathcal{P}(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

One-Photon-Exchange Potentials

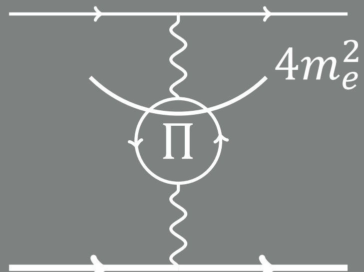


$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \frac{a \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

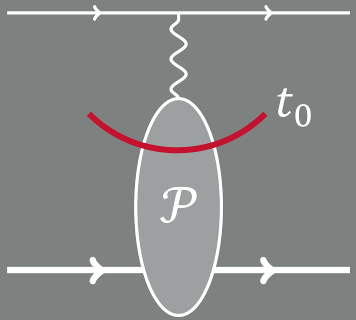


$$E_{2P-2S}^{\langle \mathrm{OPE} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} \mathrm{d}t \frac{\mathrm{Im}\mathcal{P}(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

One-Photon-Exchange Potentials



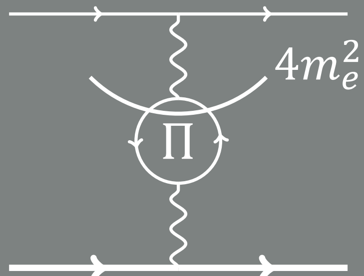
$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{a \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$



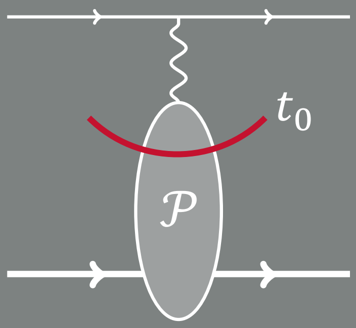
$$E_{2P-2S}^{\langle \mathrm{OPE} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\mathcal{P}(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

$$\kappa = \frac{m_r}{\sqrt{t_0}} Z\alpha$$

One-Photon-Exchange Potentials



$$E^{\langle \text{eVP} \rangle}_{2P-2S} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{a \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

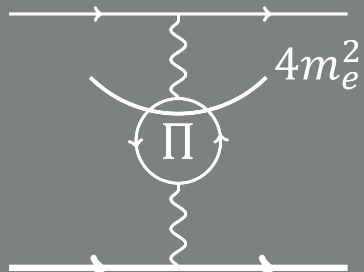


$$E^{\langle \text{OPE} \rangle}_{2P-2S} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\mathcal{P}(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

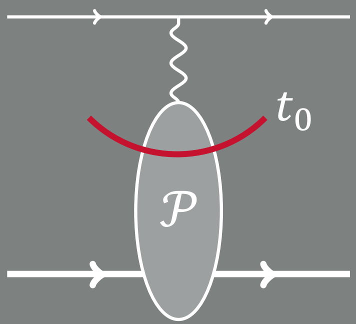
$$\kappa = \frac{m_r}{\sqrt{t_0}} Z\alpha$$

larger m_r, smaller t_0 } larger κ → enhancement!

One-Photon-Exchange Potentials



$$E_{2P-2S}^{\langle \mathrm{eVP} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{4m_e^2}^{\infty} \mathrm{d}t \, \frac{a \, \mathrm{Im}\Pi(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$



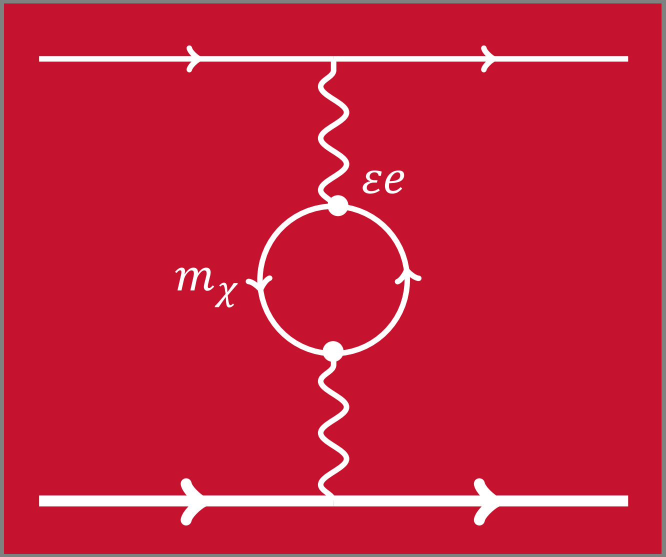
$$E_{2P-2S}^{\langle \mathrm{OPE} \rangle} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} \mathrm{d}t \, \frac{\mathrm{Im}\mathcal{P}(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

$\kappa = \frac{m_r}{\sqrt{t_0}} Z\alpha$

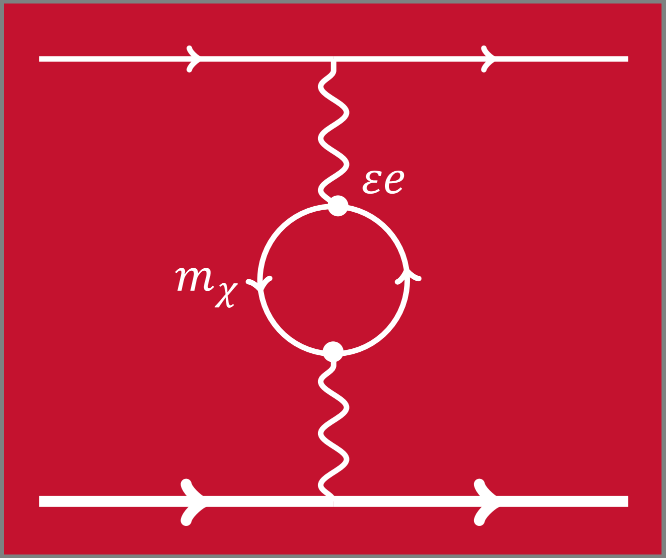
larger m_r
smaller t_0

Contributions can be enhanced depending on the system's m_r!

Dark Matter Fermion



Dark Matter Fermion



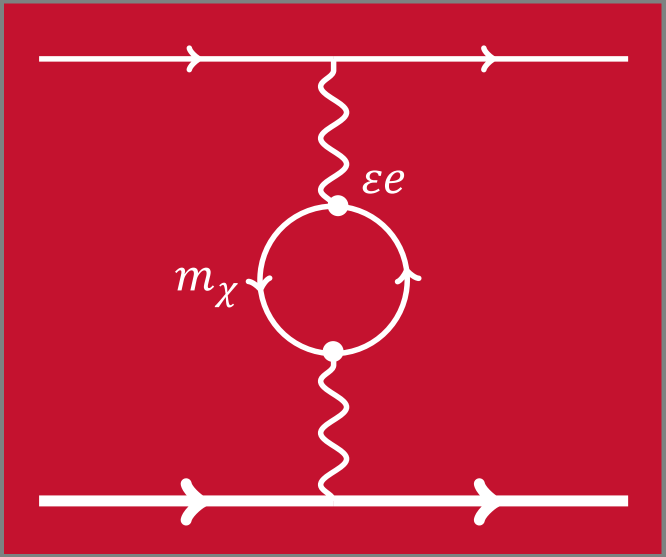
Lamb Shift Measurements

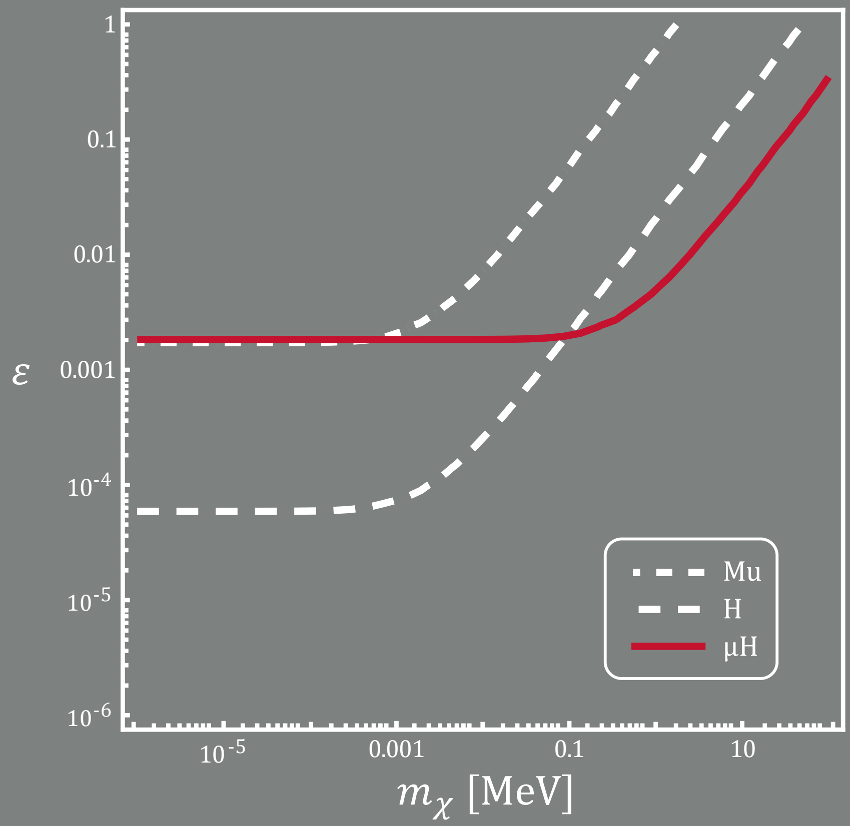
Mu: 4.3309(105) μeV

H: 4.37483(1) μeV

μH: 202.3706(23) meV

Dark Matter Fermion





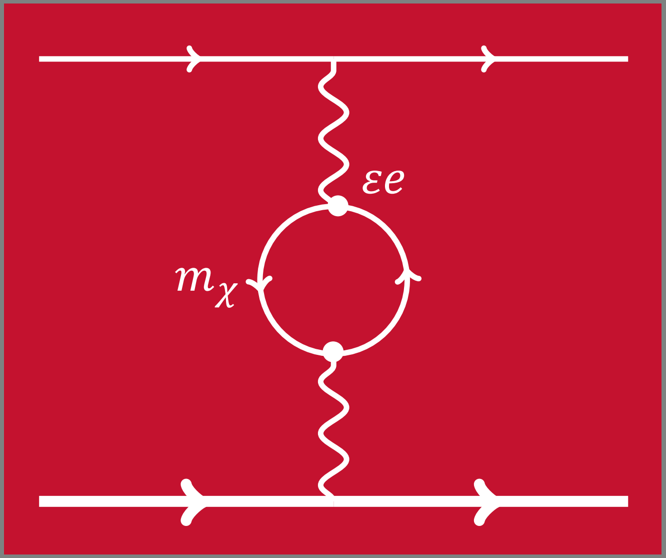
Lamb Shift Measurements

Mu: 4.3309(105) μeV

H: 4.37483(1) μeV

μH: 202.3706(23) meV

Dark Matter Fermion

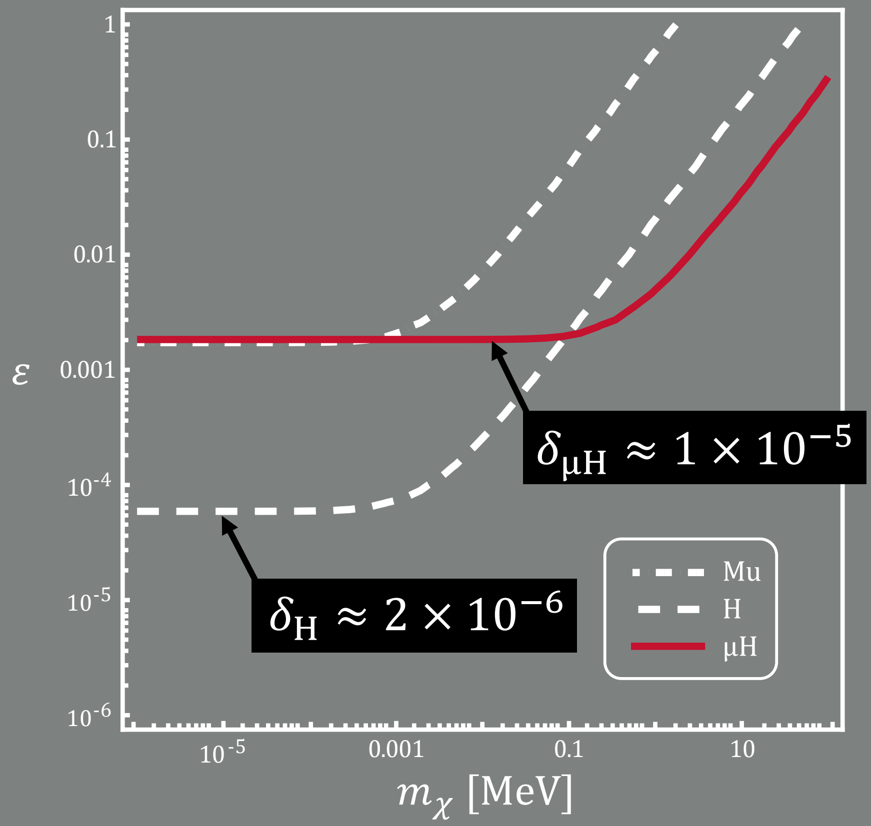


Lamb Shift Measurements

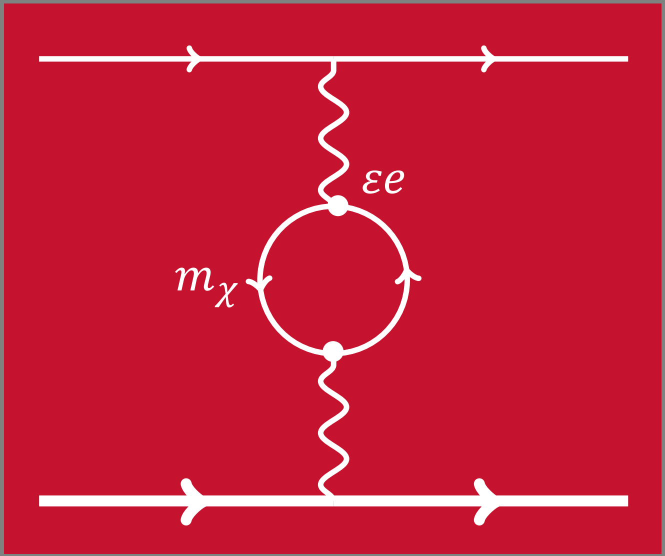
Mu: 4.3309(105) μeV

H: 4.37483(1) μeV

μH: 202.3706(23) meV

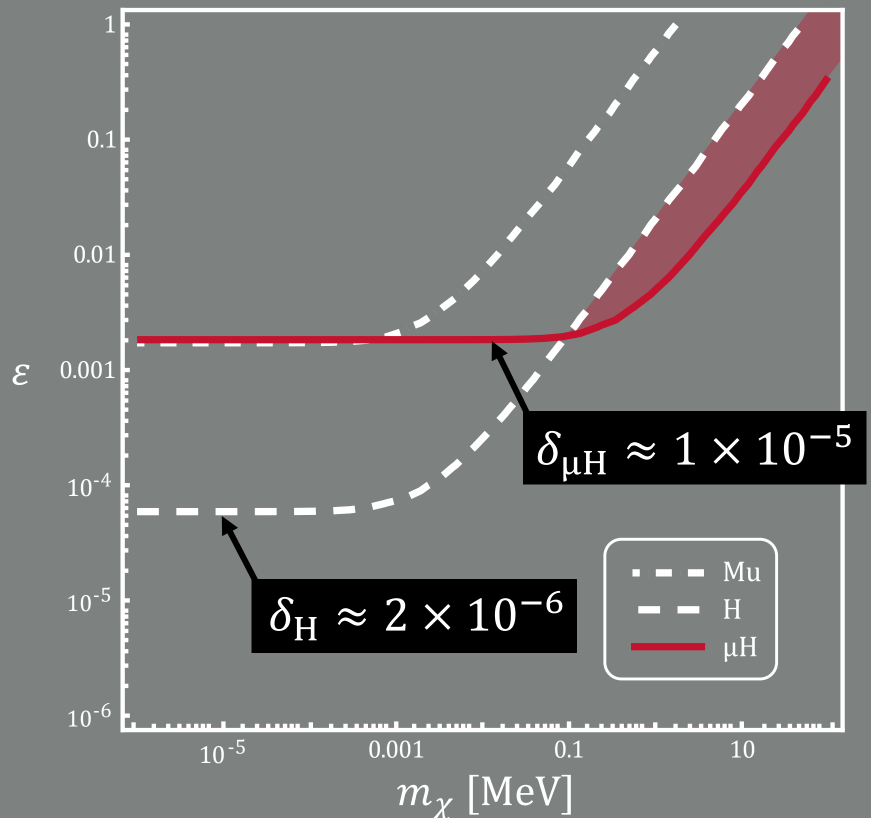


Dark Matter Fermion

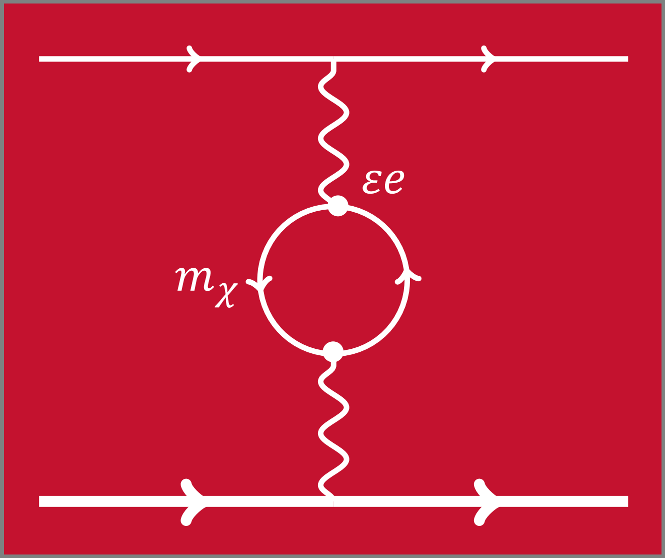


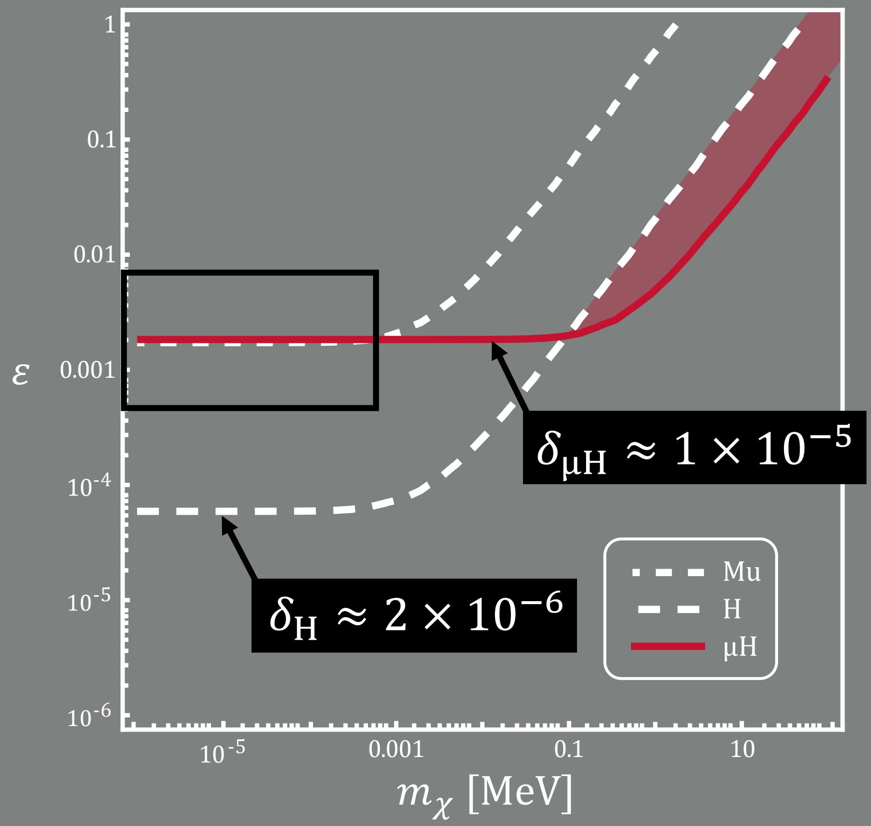
Lamb Shift Measurements

Mu: 4.3309(105) μeV
H: 4.37483(1) μeV
μH: 202.3706(23) meV



Dark Matter Fermion





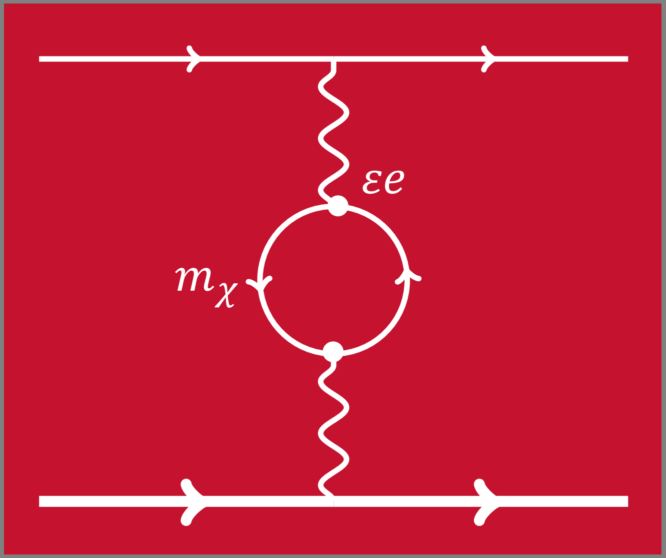
Lamb Shift Measurements

Mu: 4.3309(105) μeV

H: 4.37483(1) μeV

μH: 202.3706(23) meV

Dark Matter Fermion

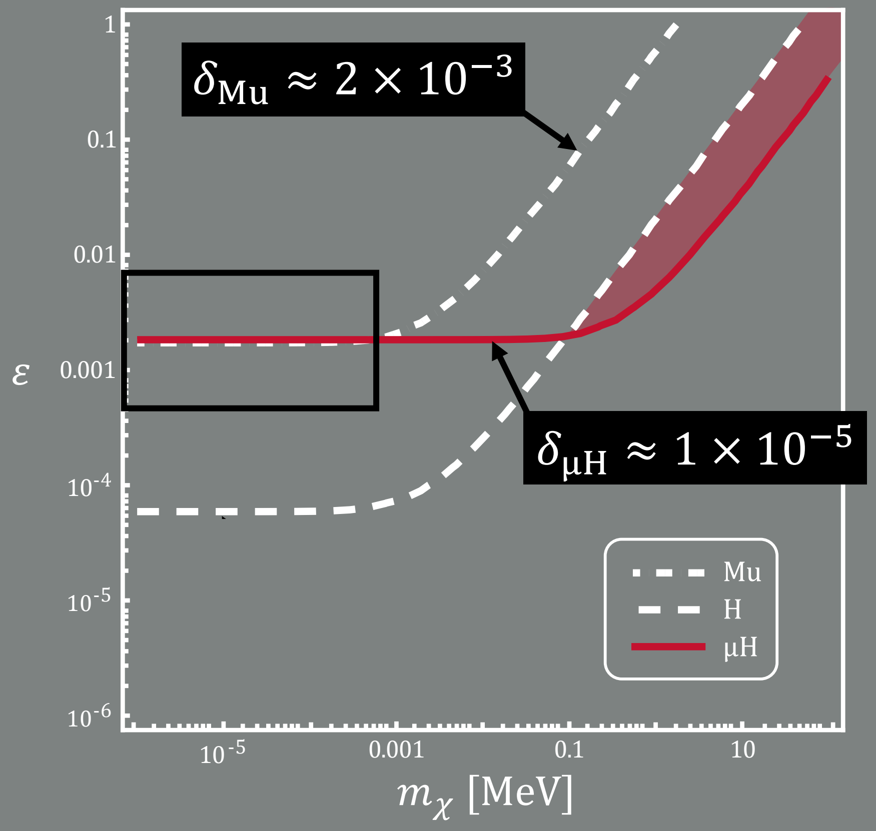


Lamb Shift Measurements

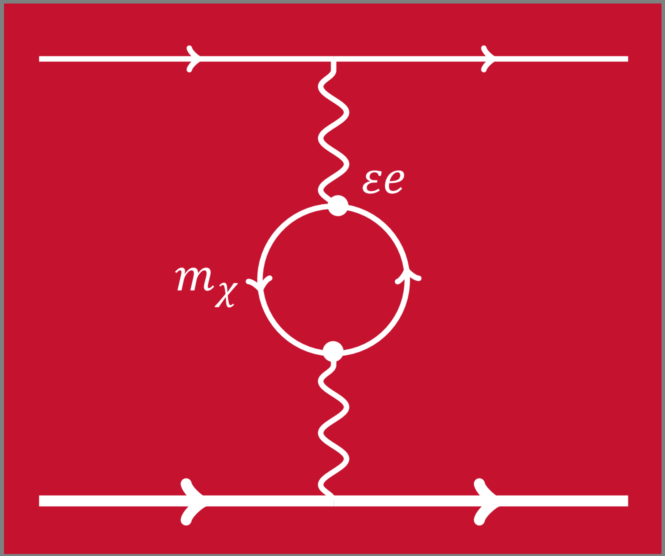
Mu: 4.3309(105) μeV

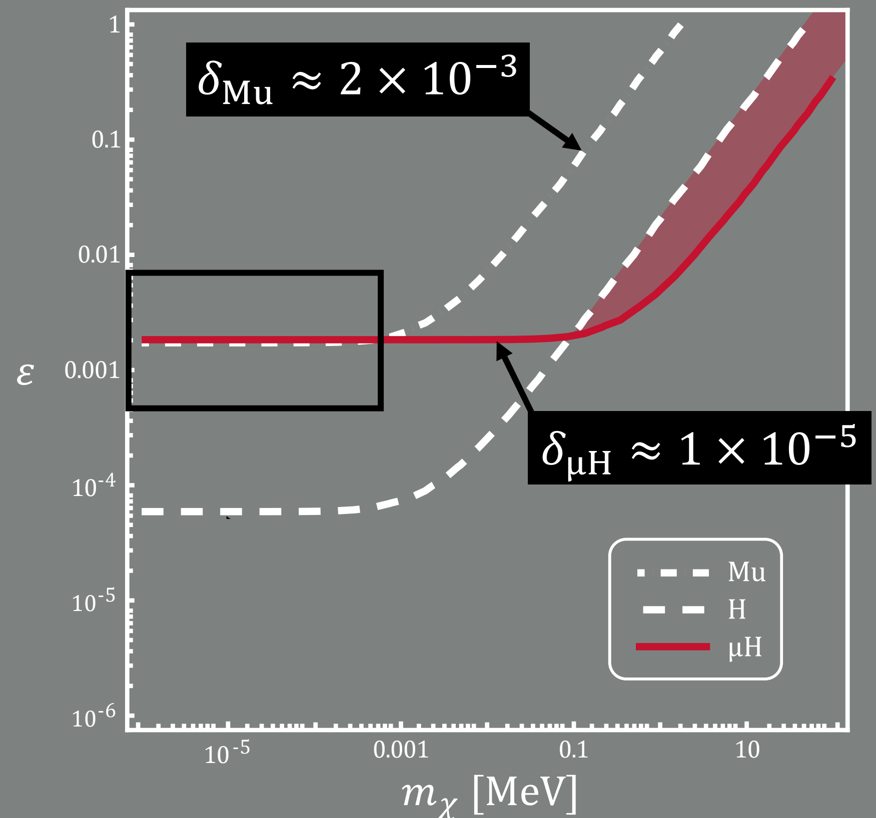
H: 4.37483(1) μeV

μH: 202.3706(23) meV



Dark Matter Fermion





Lamb Shift Measurements

Mu: 4.3309(105) μeV

H: 4.37483(1) μeV

μH: 202.3706(23) meV

Sensitivity depends on experimental precision, Bohr radius, BSM parameters

Finite-Size Corrections

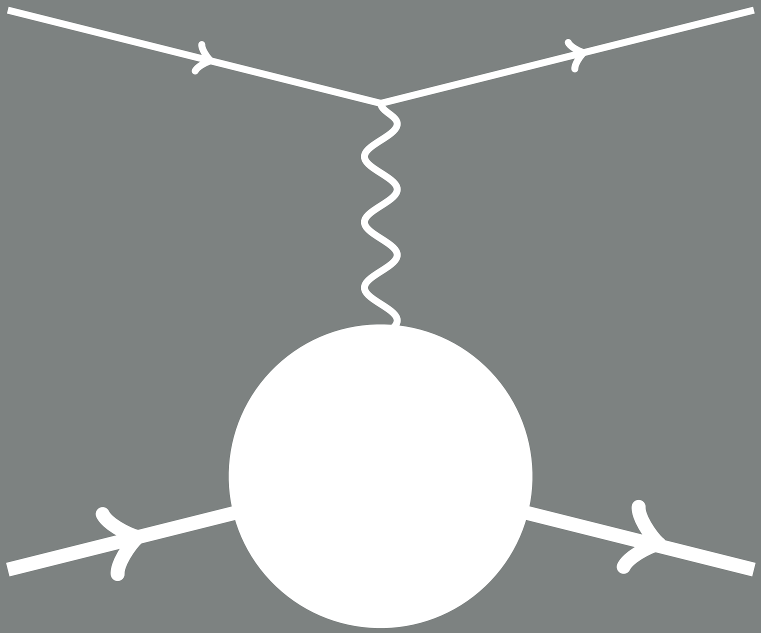
$$E_{2P-2S}^{\langle \mathrm{FS} \rangle} = \int_0^\infty \mathrm{d}Q \, w(Q) \, G_E(Q^2)$$

DOI:10.1103/PhysRevA.91.040502

Finite-Size Corrections

$$E_{2P-2S}^{\langle \mathrm{FS} \rangle} = \int_0^\infty \mathrm{d}Q\, w(Q)\, G_E(Q^2)$$

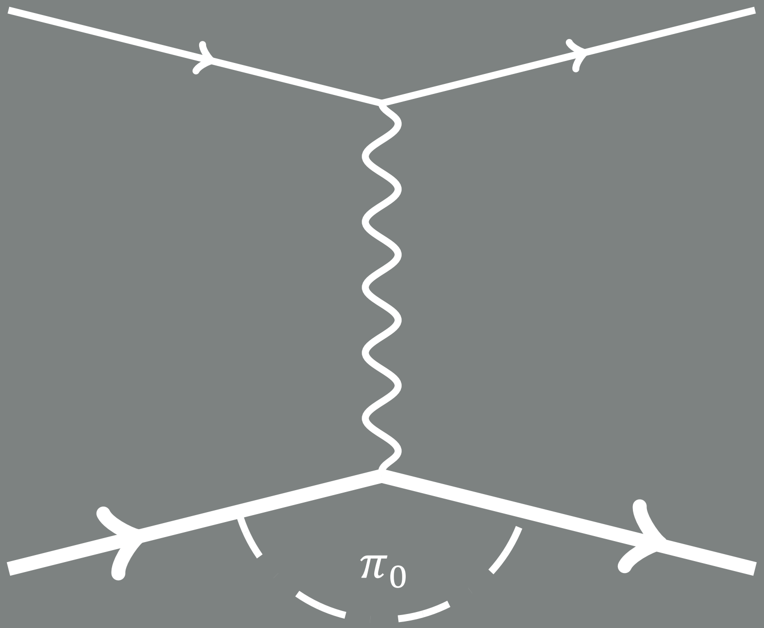
DOI:10.1103/PhysRevA.91.040502



Finite-Size Corrections

$$E_{2P-2S}^{\langle \mathrm{FS} \rangle} = \int_0^\infty \mathrm{d}Q\, w(Q)\, G_E(Q^2)$$

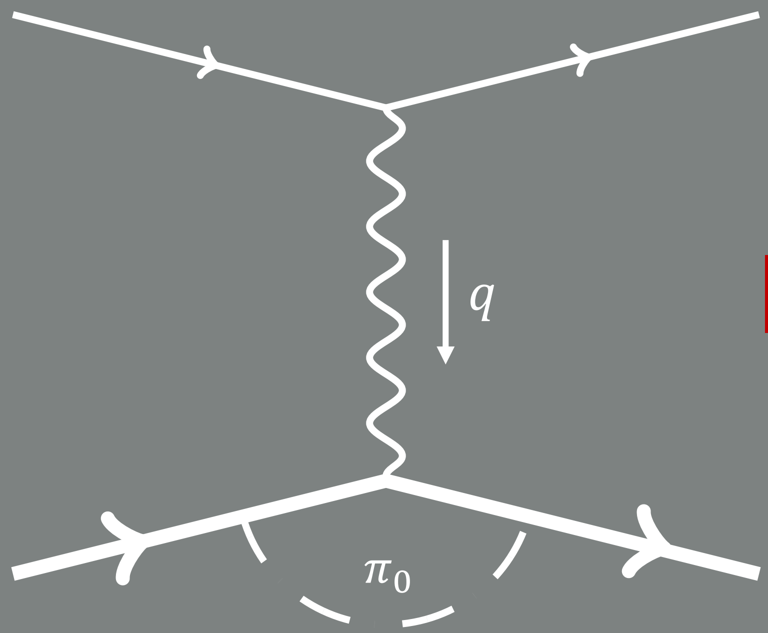
DOI:10.1103/PhysRevA.91.040502



Finite-Size Corrections

$$E_{2P-2S}^{\langle \mathrm{FS} \rangle} = \int_0^\infty \mathrm{d}Q \, w(Q) \, G_E(Q^2)$$

DOI:10.1103/PhysRevA.91.040502



$Q^2 = -q^2$

Finite-Size Corrections

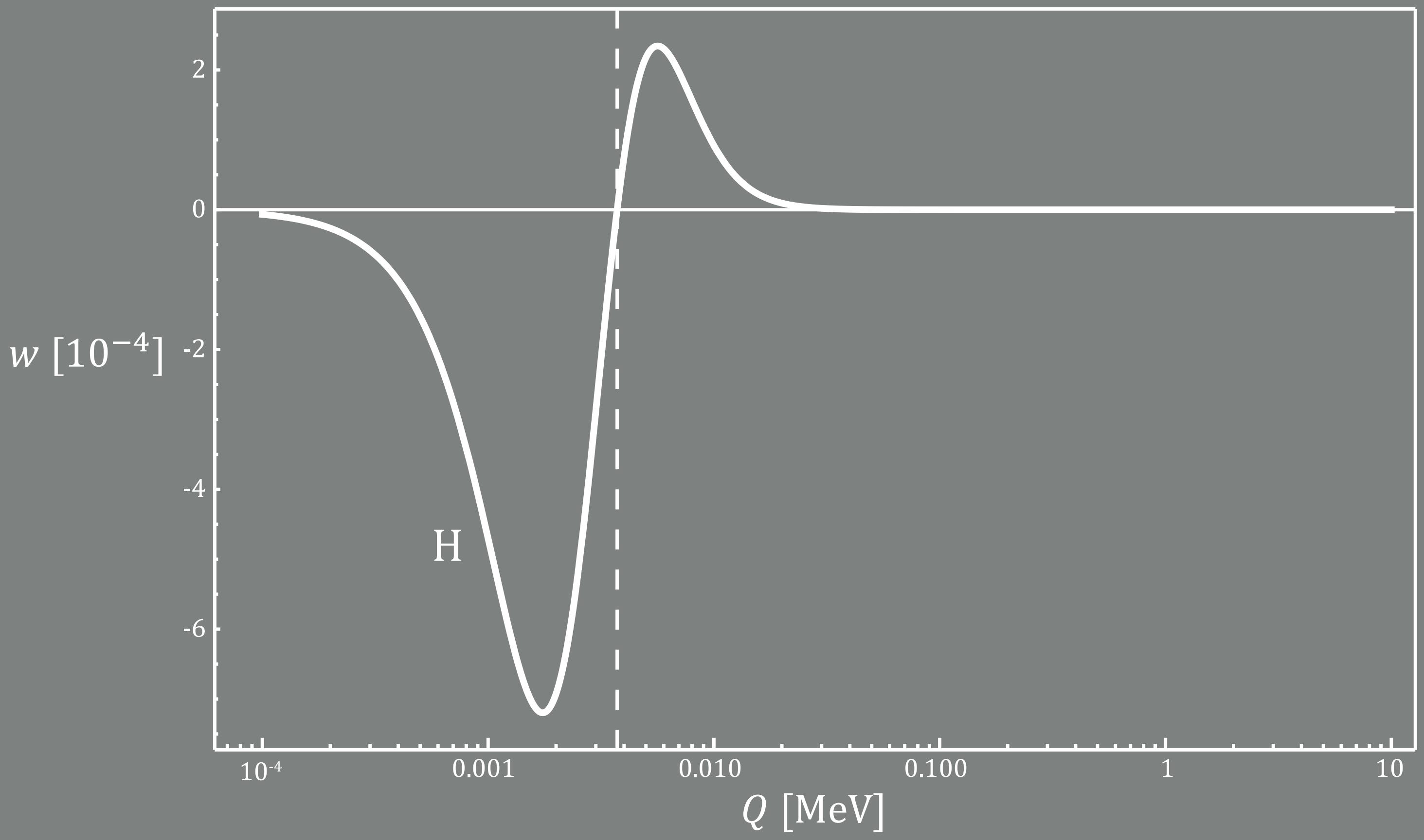
$$E^{\langle \mathrm{FS} \rangle}_{2P-2S} = \int_0^\infty \mathrm{d}Q \, w(Q) \, G_E(Q^2)$$

DOI:10.1103/PhysRevA.91.040502

Finite-Size Corrections

$$E_{2P-2S}^{\langle \mathrm{FS} \rangle} = \int_0^\infty \mathrm{d}Q \, w(Q) \, G_E(Q^2)$$

DOI:10.1103/PhysRevA.91.040502

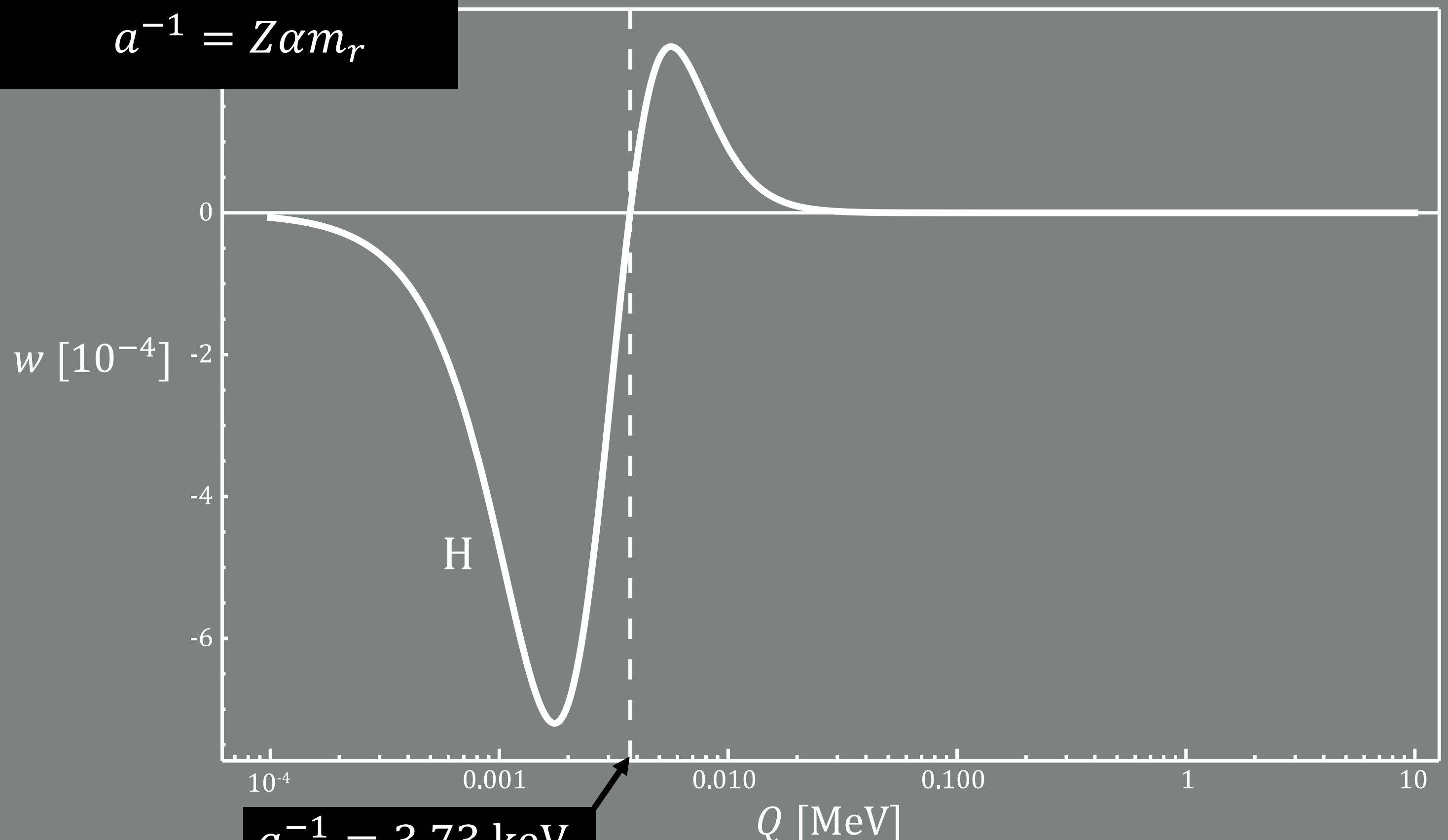


Finite-Size Corrections

$$E_{2P-2S}^{\langle \mathrm{FS} \rangle} = \int_0^\infty \mathrm{d}Q\, w(Q)\, G_E(Q^2)$$

DOI:10.1103/PhysRevA.91.040502

Inv. Bohr radius:
$a^{-1} = Z\alpha m_r$



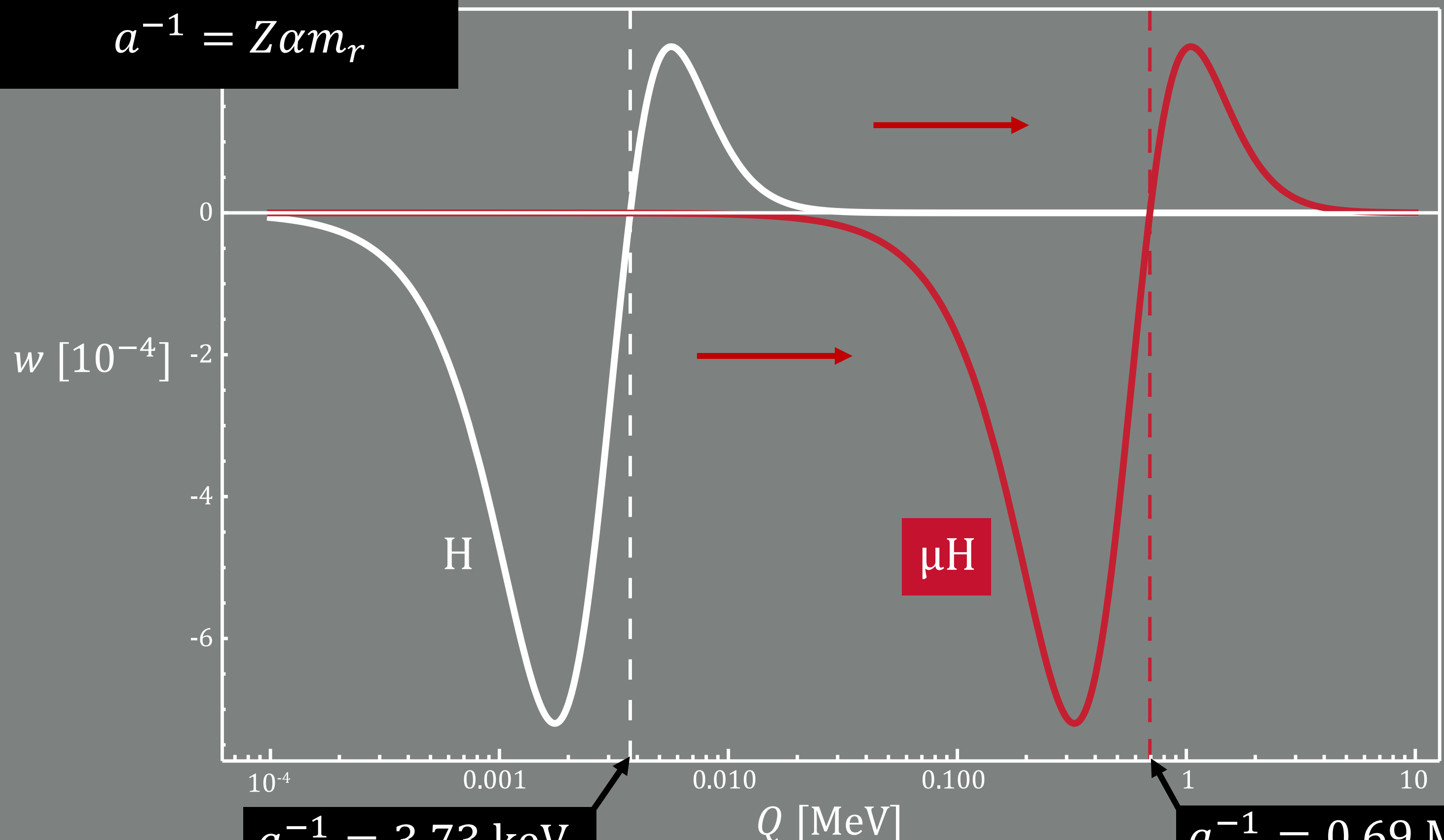
$a_{\mathrm{H}}^{-1} = 3.73\ \mathrm{keV}$

Finite-Size Corrections

$$E^{\langle \mathrm{FS} \rangle}_{2P-2S} = \int_0^\infty \mathrm{d}Q\, w(Q)\, G_E(Q^2)$$

DOI:10.1103/PhysRevA.91.040502

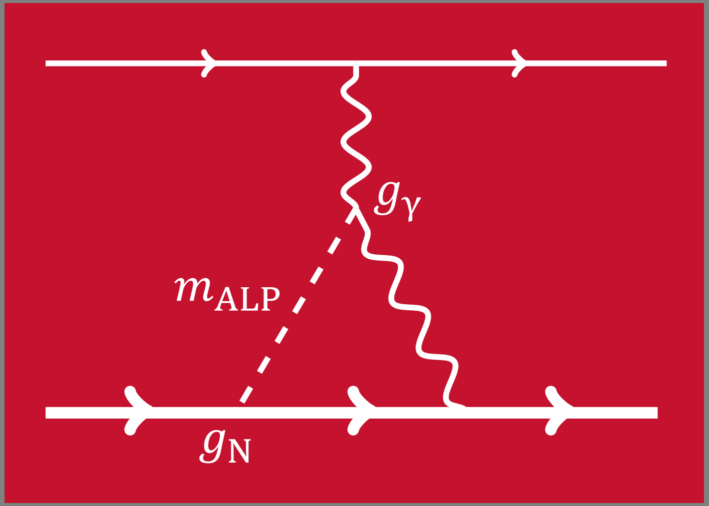
Inv. Bohr radius:
$a^{-1} = Z\alpha m_r$



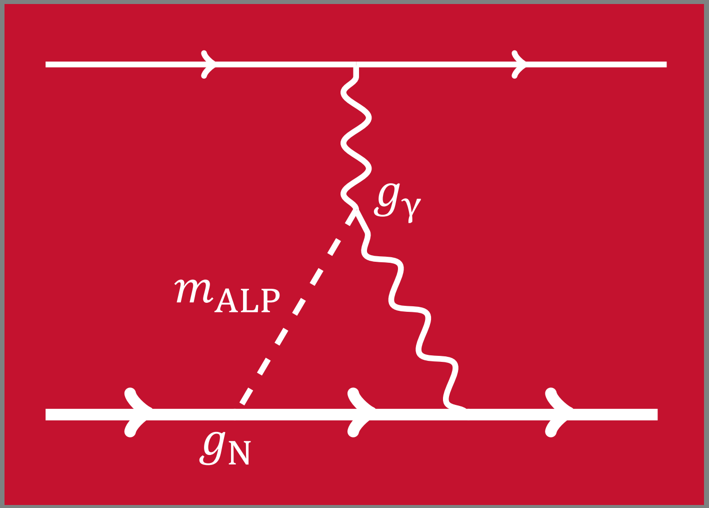
$a_{\mathrm{H}}^{-1} = 3.73$ keV

$a_{\mu\mathrm{H}}^{-1} = 0.69$ MeV

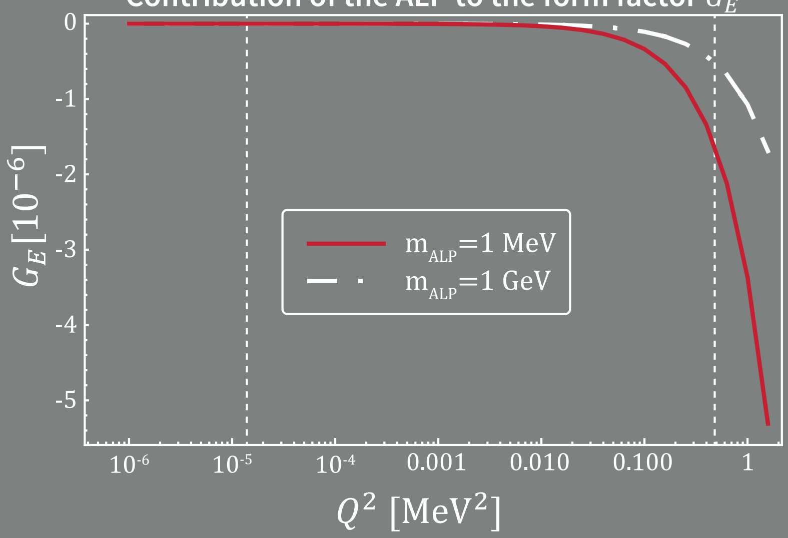
Axion-Like Particle



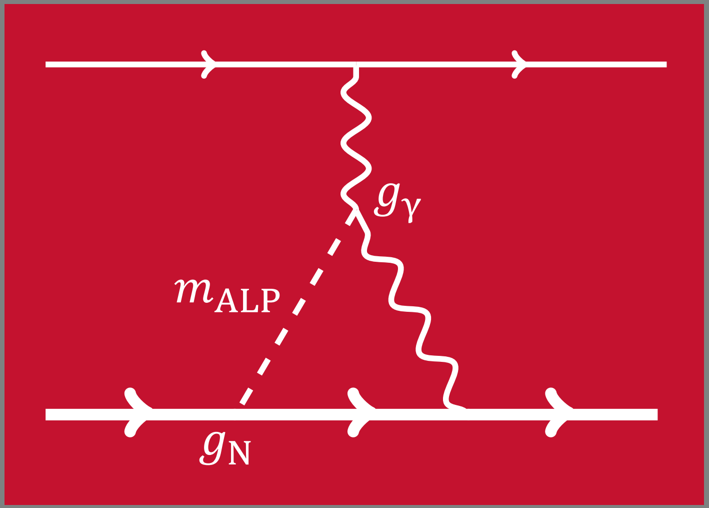
Axion-Like Particle



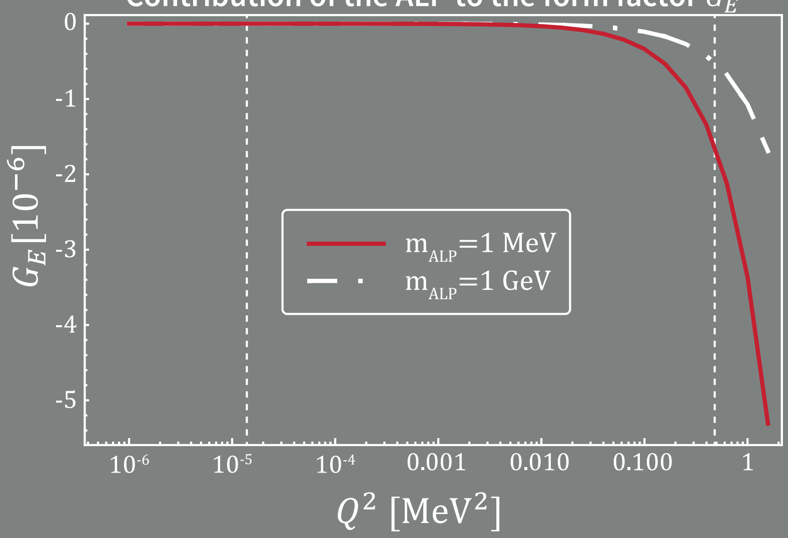
Contribution of the ALP to the form factor G_E

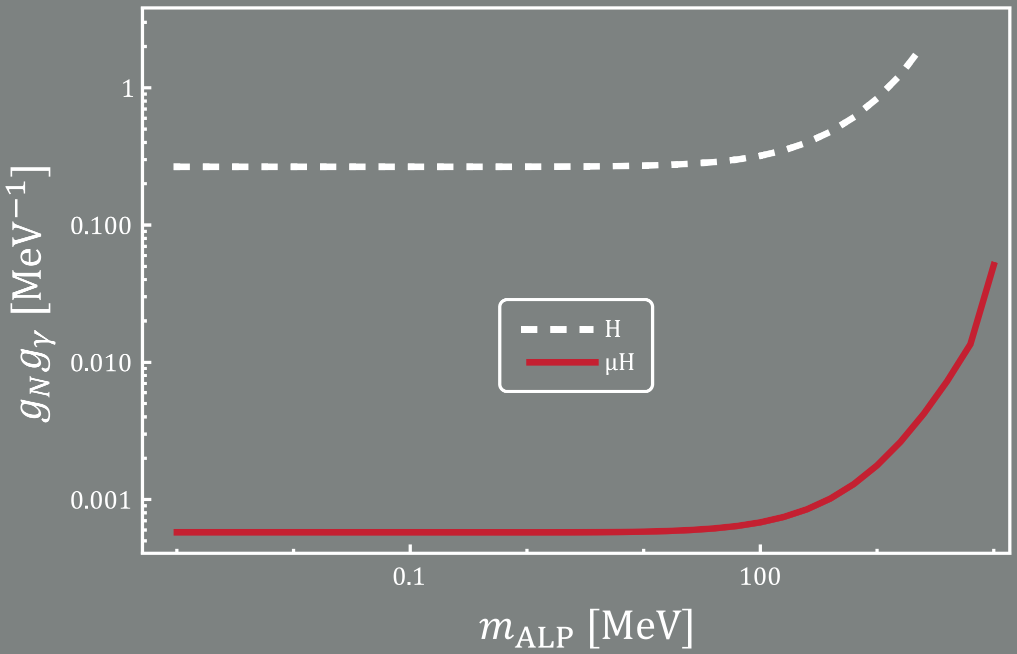


Axion-Like Particle

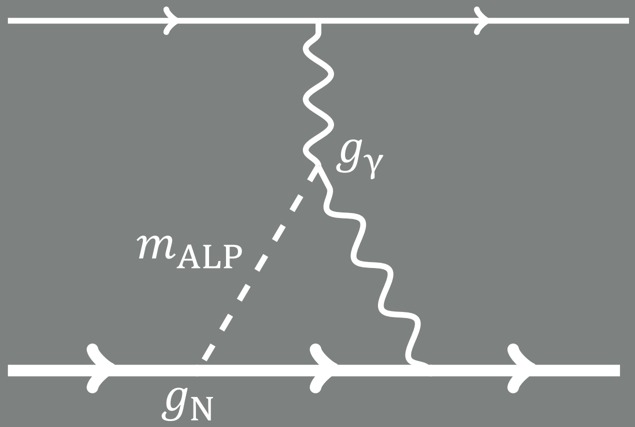


Contribution of the ALP to the form factor G_E

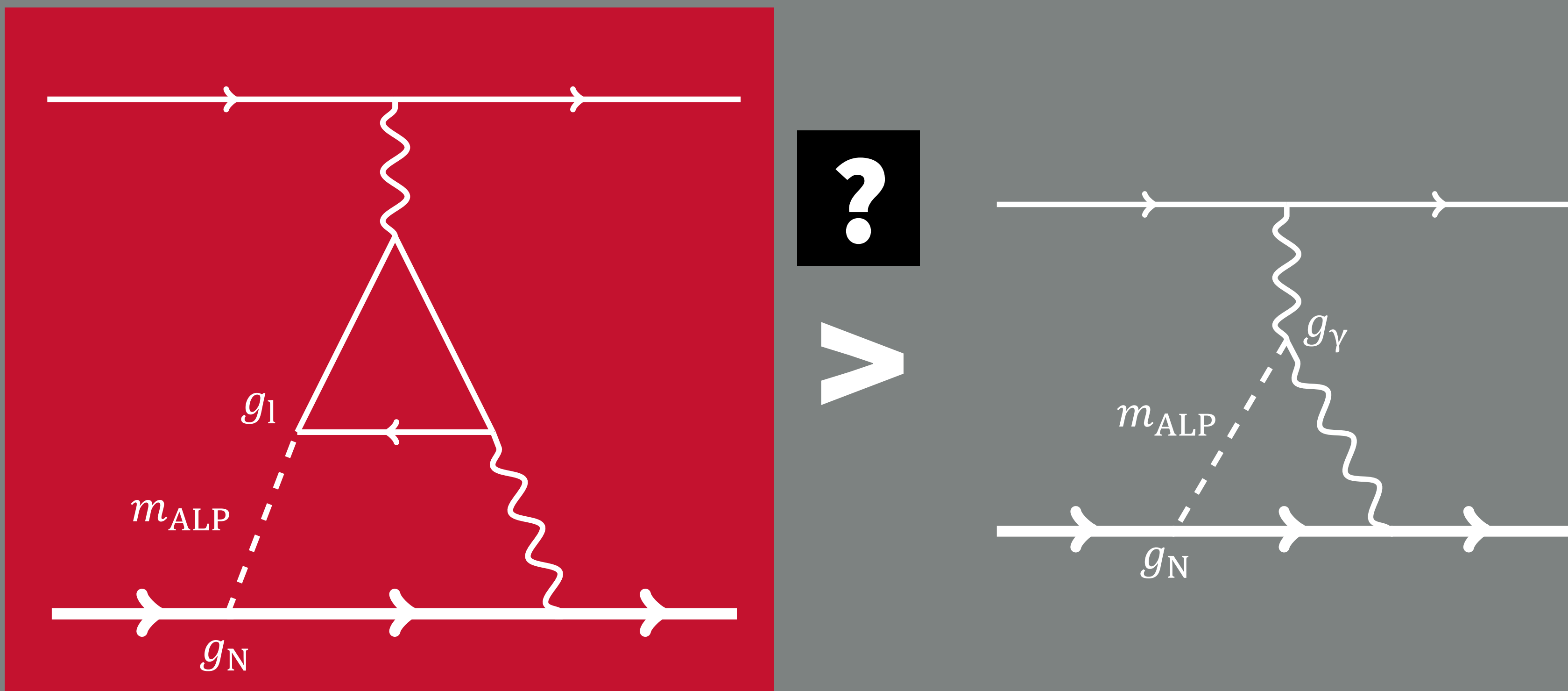




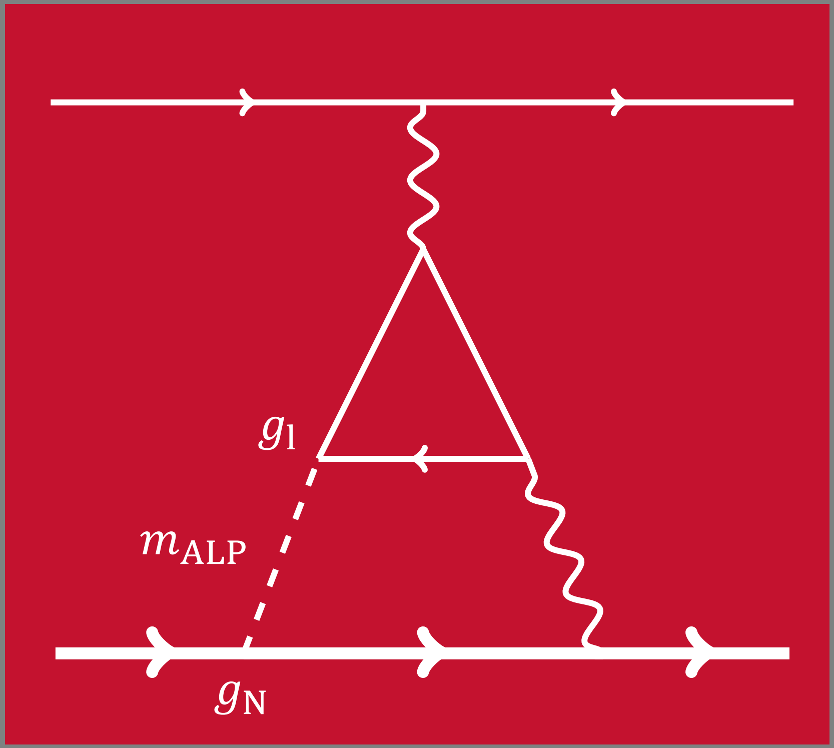
Axion-Like Particle

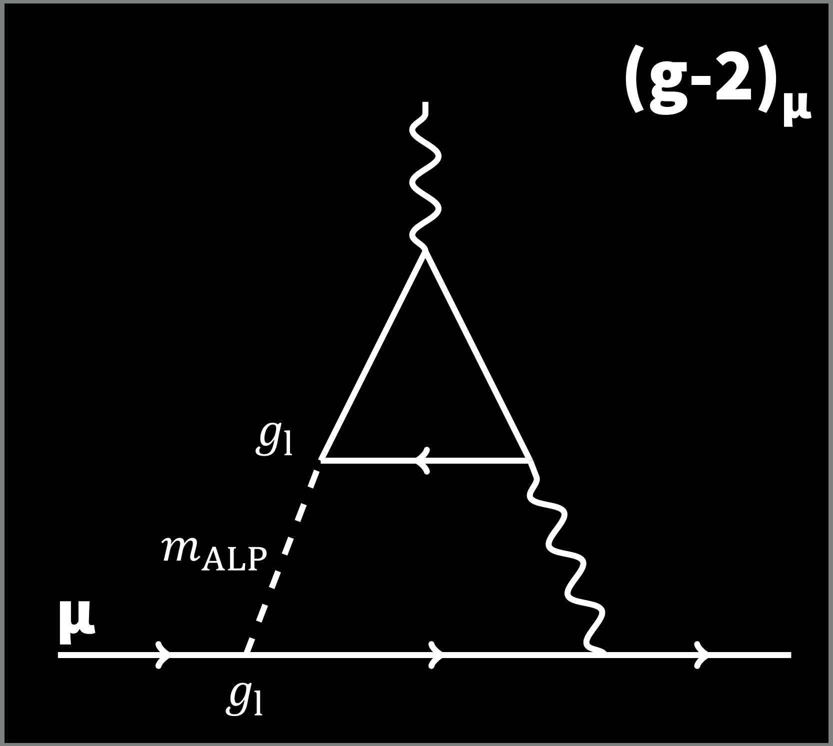


Axion-Like Particle



Axion-Like Particle





Conclusions

- **Precision atomic spectroscopy holds potential for New Physics searches**

Conclusions

- **Precision atomic spectroscopy holds potential for New Physics searches**

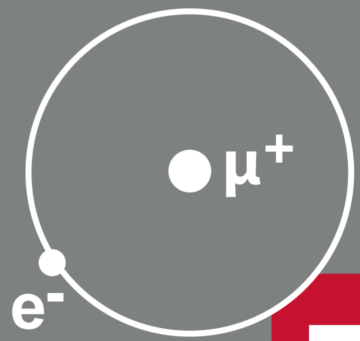
- **Sensitivity to New Physics depends on energy transition, experimental precision, (exotic) atom, BSM model**

Conclusions

- **Precision atomic spectroscopy holds potential for New Physics searches**
- **Sensitivity to New Physics depends on energy transition, experimental precision, (exotic) atom, BSM model**
- **Light BSM contributions are potentially enhanced**

Conclusions

- **Precision atomic spectroscopy holds potential for New Physics searches**
- **Sensitivity to New Physics depends on energy transition, experimental precision, (exotic) atom, BSM model**
- **Light BSM contributions are potentially enhanced**
- **Variety of (exotic) systems with different scales**



Thank you!