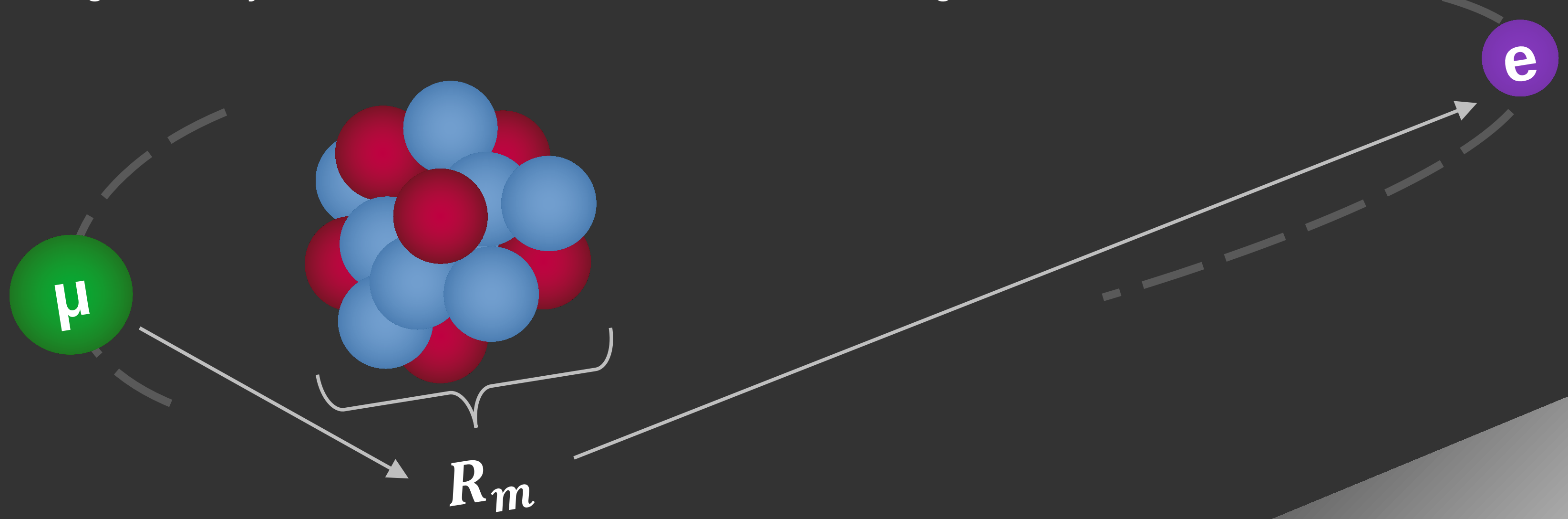
The role of muonic atoms in constraining nuclear structure.

AIP Congress, 2024

James Vandeleur,
George Sanamyan, Odile Smits, Ben Roberts, Jacinda Ginges.



The University of Queensland
Australia

(Heavy) Atoms as laboratories

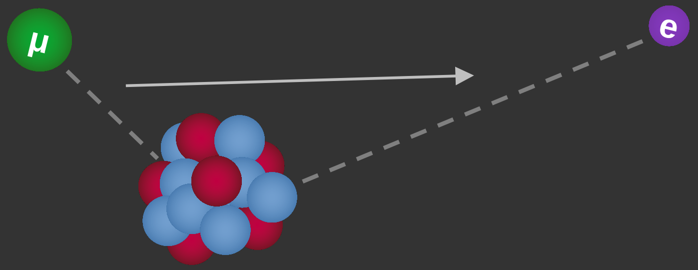
Atomic and nuclear theory allow us to pursue:

- CP-violating Electric Dipole Moments
- Atomic Parity Violation
- Nuclear structure
- Atomic clocks

Atomic hyperfine structure is a playground for testing atomic and nuclear theory.

Two key results

From muonic atom hyperfine experiment



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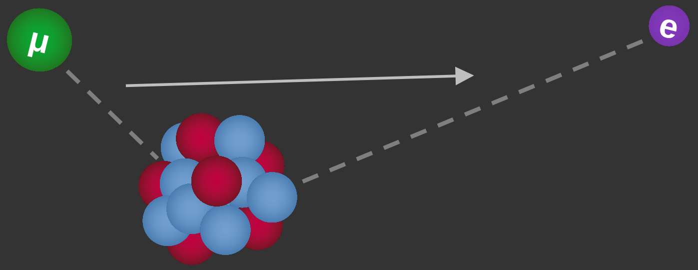
From muonic atom hyperfine experiment



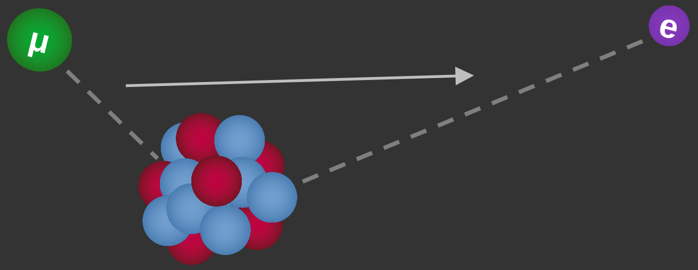
Absolute value of the finite magnetisation distribution in ^{199}Hg.

- Test of famous rule that relates this to the magnetic moments of isotopes.

Vandeleur, Sanamyan, Roberts, Ginges, (2024), arXiv:2411.09912.

Two key results

From muonic atom hyperfine experiment



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First determination of **Nuclear Polarisation** effect.

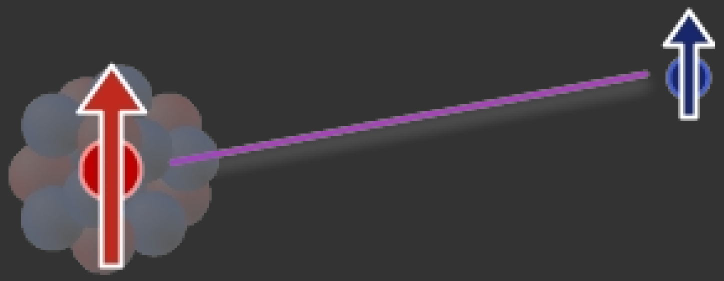
- New heavy muonic atom program at Paul Scherrer Institute - after ~50 years!
- Opens up study of nuclear magnetisation distribution.

Vandeleur, Sanamyan, Smits, Valuev, Oreshkina, Ginges, (2024), arXiv:2408.16516, under review at PRL.

The Hyperfine Anomaly

The hyperfine interaction.

$$\mathcal{A} \propto \langle \mu \cdot \mathbf{B} \rangle$$

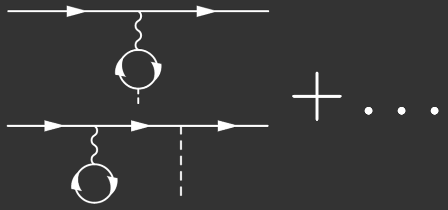


$$\mathcal{A} = \mathcal{A}_{\text{point}} + \mathcal{A}_{\text{charge}} + \mathcal{A}_{\text{mag}} + \mathcal{A}_{\text{QED}} + \mathcal{A}_{\text{NP}}$$

The Hyperfine Anomaly

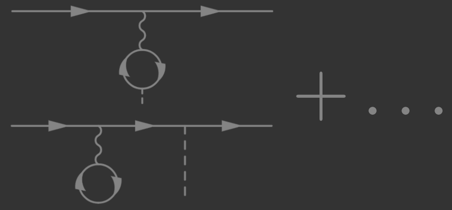
$$\mathcal{A} = \overbrace{\mathcal{A}_{\text{point}} + \mathcal{A}_{\text{charge}}}^{\mathcal{A}_0} + \mathcal{A}_{\text{mag}} + \mathcal{A}_{\text{QED}} + \mathcal{A}_{\text{NP}}$$

The Hyperfine Anomaly



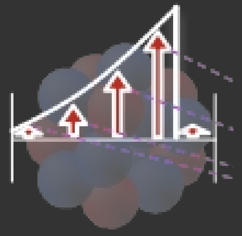
$$\mathcal{A} = \overbrace{\mathcal{A}_{\rm point} + \mathcal{A}_{\rm charge}}^{\mathcal{A}_0} + \mathcal{A}_{\rm mag} + \mathcal{A}_{\rm QED} + \mathcal{A}_{\rm NP}$$

The Hyperfine Anomaly



$$\mathcal{A} = \overbrace{\mathcal{A}_{\text{point}} + \mathcal{A}_{\text{charge}}}^{\mathcal{A}_0} + \underbrace{\mathcal{A}_{\text{mag}}}_{\text{BW}} + \mathcal{A}_{\text{QED}} + \mathcal{A}_{\text{NP}}$$

$\mu F(r)$



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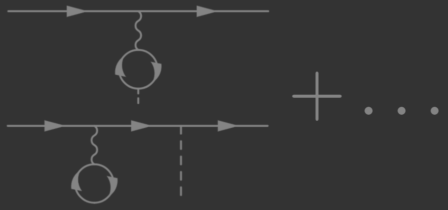

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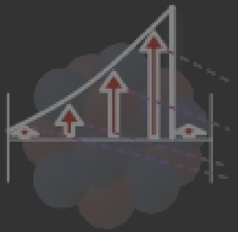

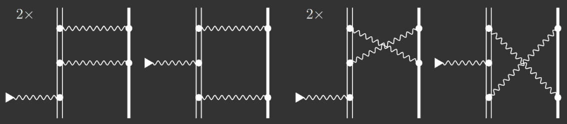

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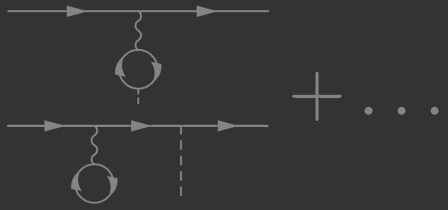

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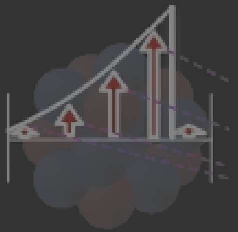
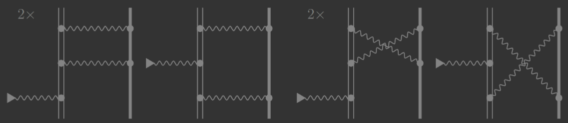
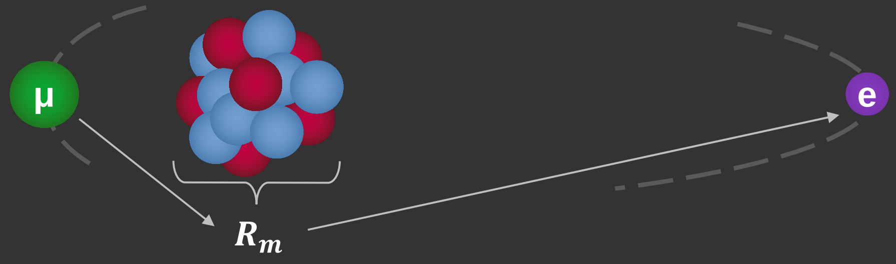




Using muonic atoms

$$\mathcal{A}_{\mathrm{BW}}^{(\mathrm{exp})} = \mathcal{A}_{\mathrm{exp}} - \mathcal{A}_0 - \mathcal{A}_{\mathrm{QED}}$$



Elizarov, Shabaev, Oreshkina, Tupitsyn, St¨ohlker, Opt. Spectrosc. 100, 361 (2006)
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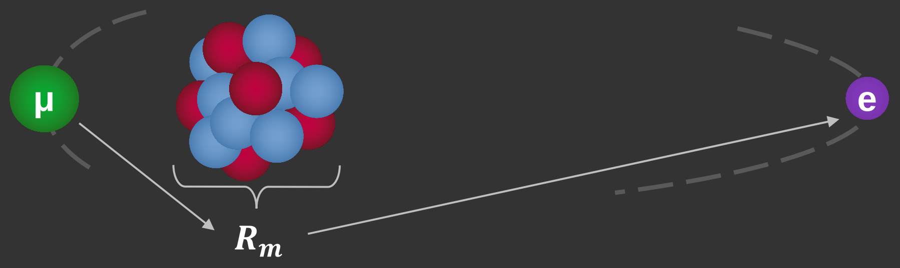

$$\mathcal{A}_{\rm BW}^{(\rm exp)} = \mathcal{A}_{\rm exp} - \mathcal{A}_0 - \mathcal{A}_{\rm QED}$$

Fitted $R_{\rm m}$

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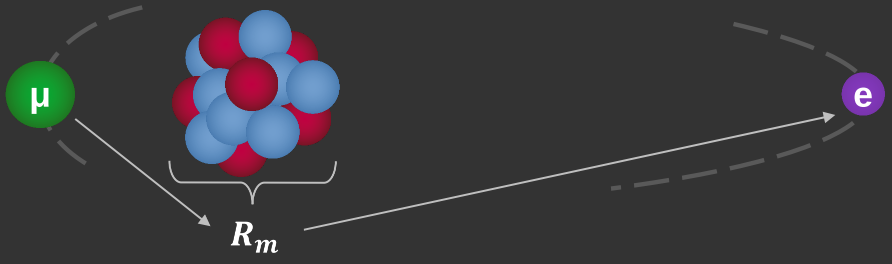

$$\mathcal{A}_{\rm BW}^{\rm (exp)} = \mathcal{A}_{\rm exp} - \mathcal{A}_0 - \mathcal{A}_{\rm QED}$$

↙

Fitted $R_{\rm m}$

↓

$\mathcal{A}_{\rm BW}$ in H-like ion

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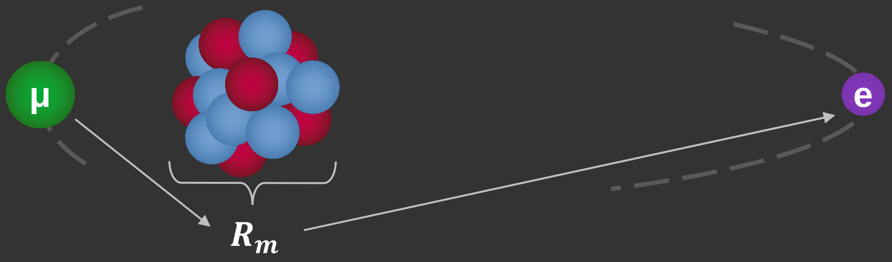

$$\mathcal{A}_{\mathrm{BW}}^{(\mathrm{exp})} = \mathcal{A}_{\mathrm{exp}} - \mathcal{A}_0 - \mathcal{A}_{\mathrm{QED}}$$

↙

Fitted R_{m}

↓

$\mathcal{A}_{\mathrm{BW}}$ in H-like ion

↓ screening

$\mathcal{A}_{\mathrm{BW}}$ in atom

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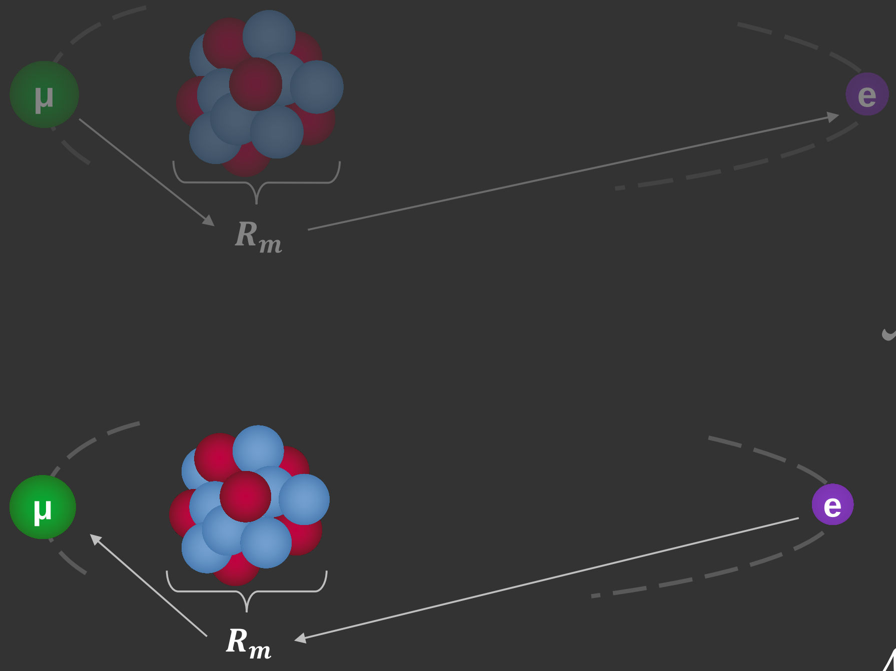
Using muonic atoms



$$\mathcal{A}_{\rm BW}^{\rm (exp)} = \mathcal{A}_{\rm exp} - \mathcal{A}_0 - \mathcal{A}_{\rm QED}$$

Fitted $R_{\rm m}$

$\mathcal{A}_{\rm BW}$ in H-like ion

screening

$\mathcal{A}_{\rm BW}$ in atom

$\mathcal{A}_{\rm BW}^{\rm (exp)}$ in H-like ion

Fitted $R_{\rm m}$

$$\mathcal{A}_{\rm NP} = \mathcal{A}_{\rm exp} - \mathcal{A}_0 - \mathcal{A}_{\rm BW} - \mathcal{A}_{\rm QED}$$

Elizarov, Shabaev, Oreshkina, Tupitsyn, St¨ohlker, Opt. Spectrosc. 100, 361 (2006)
Roberts, Ranclaud, Ginges, Phys. Rev. A 105, 052802 (2022).

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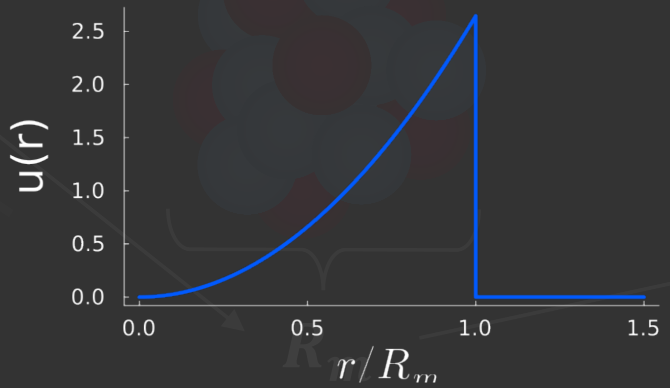
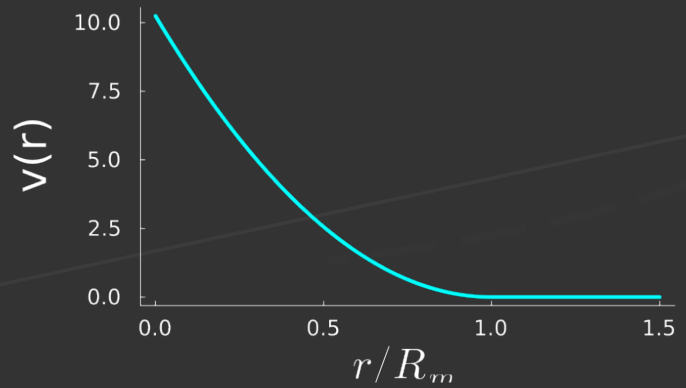
Parameterise the nucleus

Muonic measurement allows for a single parameter.

$$F(r) = \frac{\mu_N}{\mu}\left\{\left[\frac{1}{2}g_S + \left(I-\frac{1}{2}\right)g_L\right]\int_0^r dr' r'^2 u^2(r') + \left[-\frac{2I-1}{8(I+1)}g_S + \left(I-\frac{1}{2}\right)g_L\right]\int_r^\infty dr' r'^2 u^2(r')(r/r')^3\right\}$$





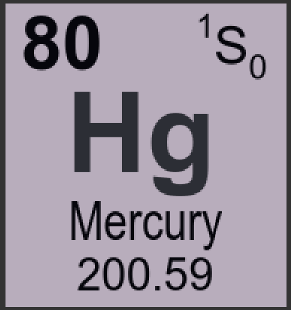
We use the single particle model with with a sweep of nucleon density functions, and a single radial parameter.

Elizarov, Shabaev, Oreshkina, Tupitsyn, St¨ohlker, Opt. Spectrosc. 100, 361 (2006)

BW effect in a single isotope, ^{199}Hg

Mercury is of great interest in contemporary atomic/nuclear physics.

- Tightest constraint on CP-violating EDM measurement in Hg
- Need for more information on nuclear Schiff moment
- Hg/Hg^{+} atomic/ion clocks



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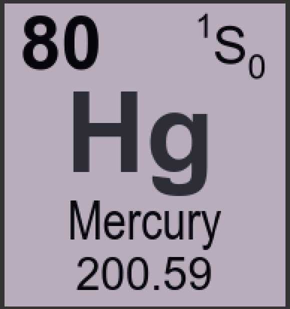


Turning to hyperfine structure,

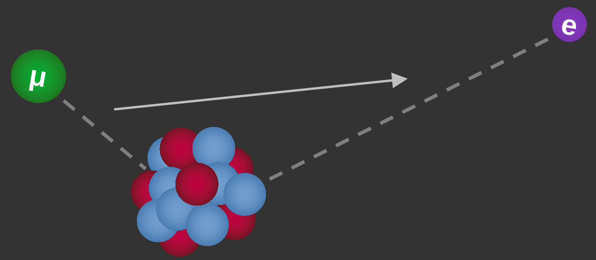
- Previously, only the relative effect known between *two* isotopes.

$$^1\Delta^2 \sim \mathcal{A}_1/\mathcal{A}_2 \simeq {}^1\delta^2 + \epsilon^{(1)} - \epsilon^{(2)}.$$

- Moskowitz Lombardi rule

$$\epsilon = \frac{-1.2 \times 10^{-2}}{|\mu|} + c \longleftarrow \text{untested!}$$

BW effect in a single isotope, ^{199}Hg



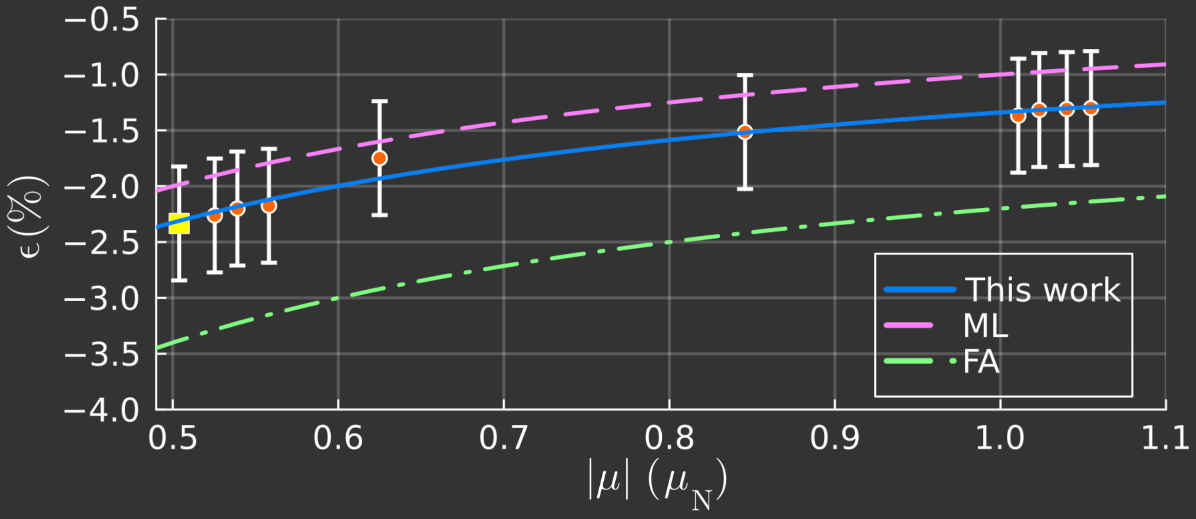
$$\epsilon = \frac{-1.2\times 10^{-2}}{|\mu|} - 3.6\times 10^{-3}$$

H-like mercury:

$$\epsilon_{^{199}\mathrm{Hg}^{79+}} = -2.39(45)\%$$

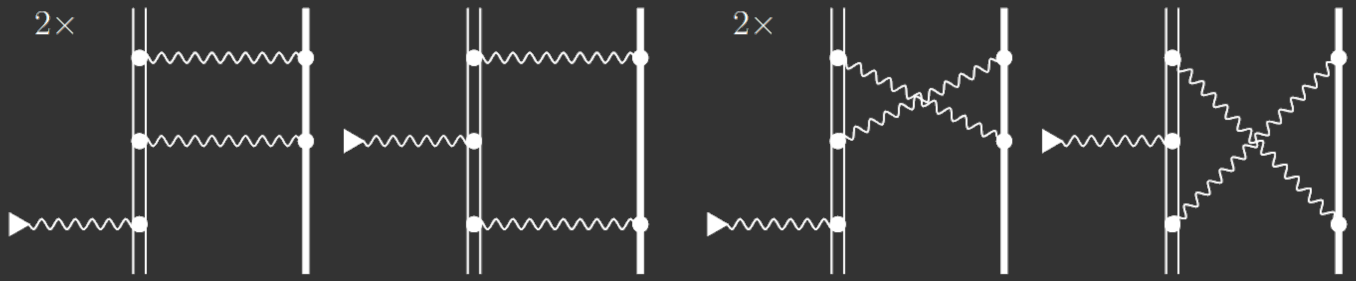
Neutral mercury:

$$\epsilon_{^{199}\mathrm{Hg}} = -2.34(44)\%$$



Vandeleur, Sanamyan, Roberts, Ginges, (2024), arXiv:2411.09912.

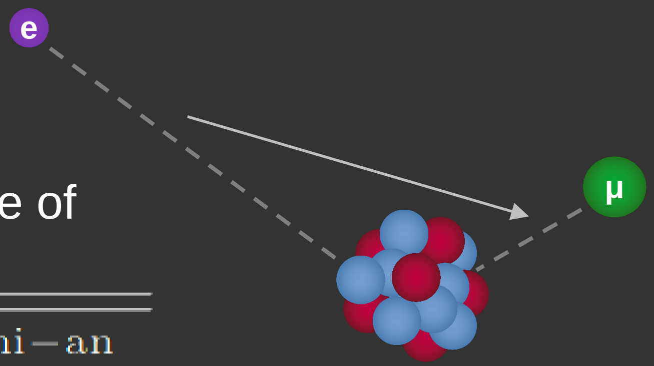
Nuclear Polarisation



$$\mathcal{A} = \mathcal{A}_0 + \mathcal{A}_{\mathrm{BW}} + \mathcal{A}_{\mathrm{QED}} + \mathcal{A}_{\mathrm{NP}}$$

- Unconstrained contribution – thought prohibitively difficult to calculate.
- Would expect much greater effect in muonic atoms – made muonic atom measurements hard to interpret.
- Limits extraction of nuclear structure properties.

Nuclear Polarisation



Nuclear polarisation contributions to hyperfine structure of muonic thallium and bismuth (keV).

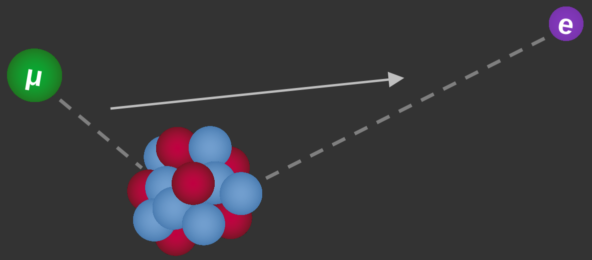
	$\mathcal{A}_{\rm NP}^{\rm semi-emp}$	$\mathcal{A}_{\rm NP}^{\rm semi-an}$
$\mu - {}^{203}\mathrm{Tl}^{80+}$	-0.037(169)	0.0024(24)
$\mu - {}^{205}\mathrm{Tl}^{80+}$	-0.081(154)	0.0024(24)
$\mu - {}^{209}\mathrm{Bi}^{82+}$	0.022(56)	0.0008(8)

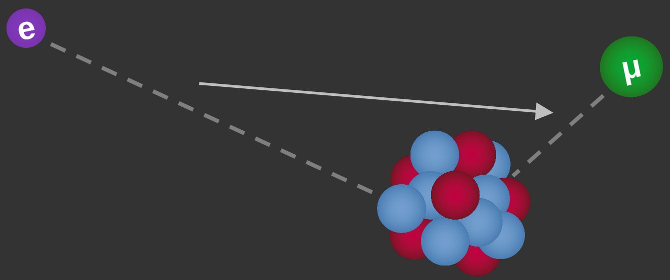
Supported semi-analytically

Encourages nuclear structure probes in muonic atoms!

Vandeleur, Sanamyan, Smits, Valuev, Oreshkina, Ginges, (2024), arXiv:2408.16516, under review at PRL.

Summary





$$\epsilon_{^{199}\mathrm{Hg}} = -2.34(44)\%$$

$$\mathcal{A}_{\mathrm{NP}}/\mathcal{A} << 1$$

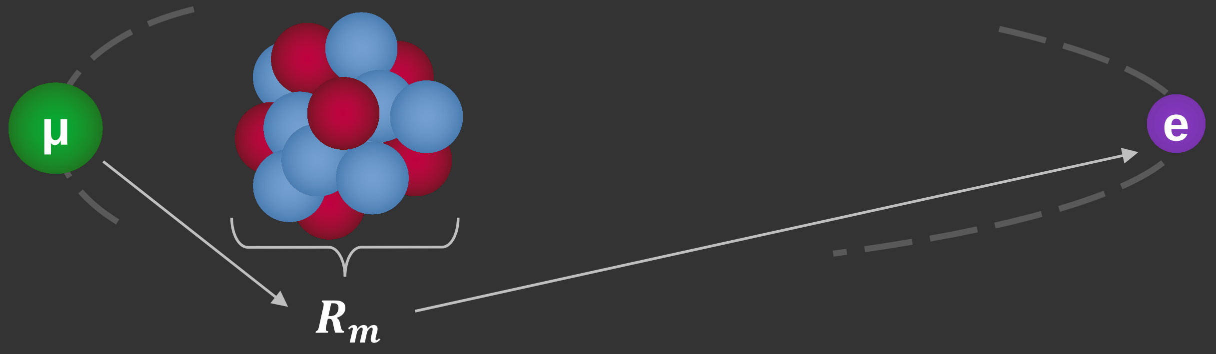
Rel. BW in ^{199}Hg provides first empirical test of the Moskowitz Lombardi rule. Improves tests of atomic calculations for EDMs, nuclear Schiff moment, nuclear structure, clocks, etc.

Vandeleur, Sanamyan, Roberts, Ginges, (2024), arXiv:2411.09912.

Smallness of the NP contribution encourages muonic atom experiment, and allows new probes of nuclear structure.

Vandeleur, Sanamyan, Smits, Valuev, Oreshkina, Ginges, (2024), arXiv:2408.16516, under review at PRL.

Thankyou.



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George Sanamyan
Odile Smits
Ben Roberts
Jacinda Ginges

Collaborators:
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Igor Valuev

Extraction of BW effect in Hg

In H-like mercury ($^{199}Hg^{79+}$)

Model	u			v			
n	0	1	2	1	2	Variance	Final Value
$R_{\rm m}$ (fm)	5.76(56)	5.16(47)	4.91(44)	8.81(96)	11.9(1.3)		
$\epsilon_{\rm BW}$ (%)	-2.33(40)	-2.26(37)	-2.24(36)	-2.50(46)	-2.61(50)	0.16	-2.39(45)

In neutral mercury (^{199}Hg) after screening,

$$\epsilon_{^{199}\mathrm{Hg}} = -2.34(44)\%$$