Constraints on **exotic spin-dependent interactions** between **matter and antimatter** from **antiprotonic helium spectroscopy**

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Plan

- Exotic potentials
- Antiprotonic helium
- Construction of wavefunctions
- Results
- Summary

Exotic potentials

- Dark matter
- Dark energy
- Strong CP problem
- Hierarchy problem

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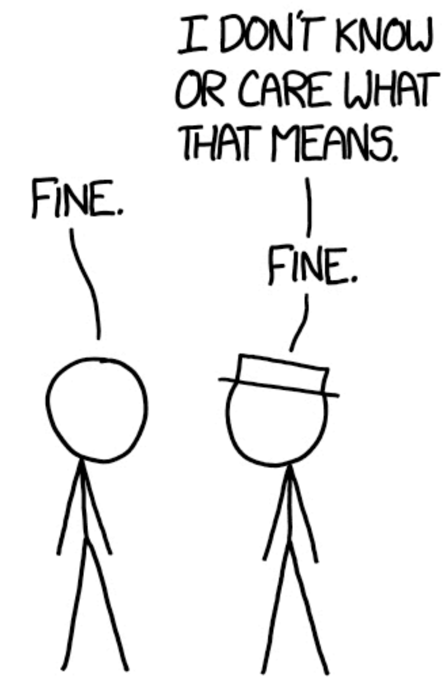
- Axions
- Familons
- Majorons
- Gravitons
- Kaluza-Klein zero modes
- Paraphotons
- Z' bosons



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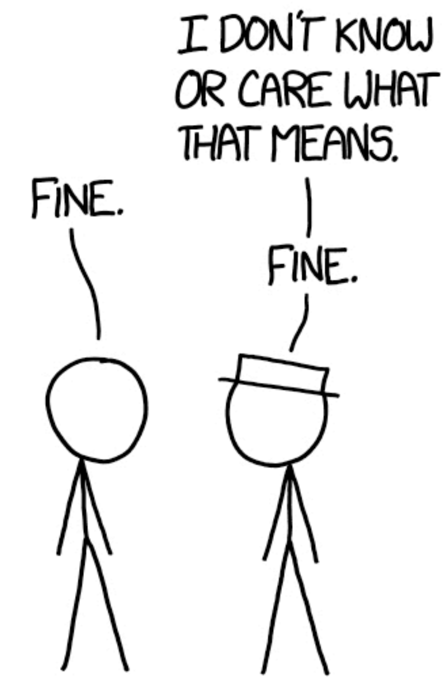

Spin-dependent interactions

Exotic potentials

- 1984 - J. E. Moody & F. Wilczek — introduced
- 2006 - B. A. Dobrescu & I. Mocioui — extended
- 2018 - P. Fadeev et.al. — reviewed

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$$V_2 = f_2^{e\overline{p}} \frac{\hbar c}{\pi} (\mathbf{s}_{\overline{p}} \cdot \mathbf{s}_e) \frac{e^{-r/\lambda}}{r},$$

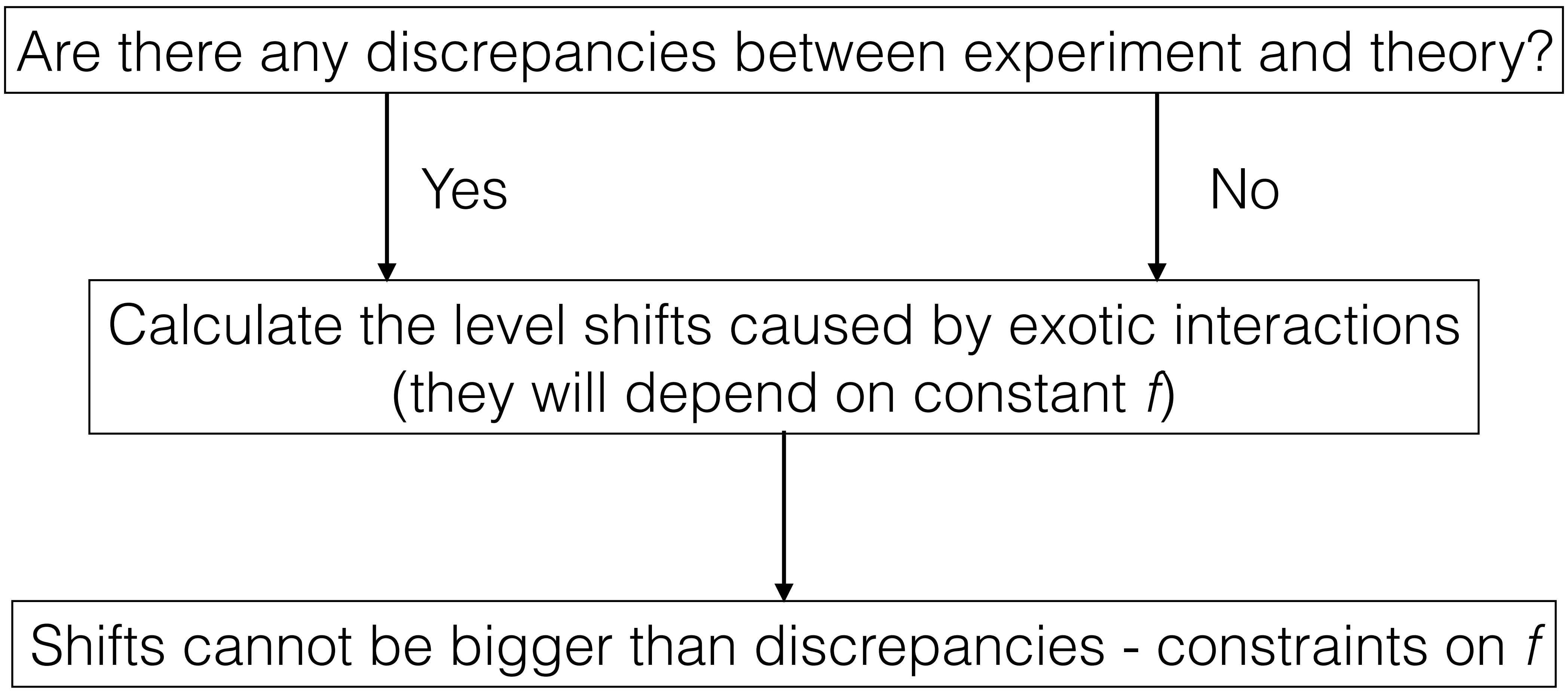
$$V_3 = f_3^{e\overline{p}} \frac{\hbar^3}{\pi m_e^2 c} \left[\mathbf{s}_{\overline{p}} \cdot \mathbf{s}_e \left(\frac{1}{\lambda r^2} + \frac{1}{r^3} + \frac{4\pi}{3} \delta^3(r) \right) - (\mathbf{s}_{\overline{p}} \cdot \mathbf{r})(\mathbf{s}_e \cdot \mathbf{r}) \left(\frac{1}{\lambda^2 r^3} + \frac{3}{\lambda r^4} + \frac{3}{r^5} \right) \right] e^{-r/\lambda},$$

$$\lambda = \frac{\hbar}{m_0 c}$$

$$V_{4+5} = f_{4+5}^{e\overline{p}} \frac{i\hbar^3}{4 m_e^2 c} \mathbf{s}_e \cdot \left[\left(\frac{m_e}{m_{\overline{p}} + m_e} \nabla_{\overline{p}} - \frac{m_{\overline{p}}}{m_{\overline{p}} + m_e} \nabla_e \right) \times \mathbf{r}, \left(\frac{1}{r^3} + \frac{1}{\lambda r^2} \right) e^{-r/\lambda} \right]_+ ,$$

$$V_8 = -f_8^{e\overline{p}} \frac{\hbar^3}{4\pi m_e^2 c} \left[\mathbf{s}_e \cdot \left(\frac{m_e}{m_{\overline{p}} + m_e} \nabla_{\overline{p}} - \frac{m_{\overline{p}}}{m_{\overline{p}} + m_e} \nabla_e \right), \left[\mathbf{s}_{\overline{p}} \cdot \left(\frac{m_e}{m_{\overline{p}} + m_e} \nabla_{\overline{p}} - \frac{m_{\overline{p}}}{m_{\overline{p}} + m_e} \nabla_e \right), \frac{e^{-r/\lambda}}{r} \right]_+ \right]_+$$

Exotic potentials



Exotic potentials

Are there any discrepancies between experiment and theory?

Yes → Calculate the level shifts caused by exotic interactions (they will depend on constant *f*)

No → Calculate the level shifts caused by exotic interactions (they will depend on constant *f*)

↓

Shifts cannot be bigger than discrepancies - constraints on *f*

PHYSICAL REVIEW A **95**, 032505 (2017)

Constraints on exotic spin-dependent interactions between electrons from helium fine-structure spectroscopy

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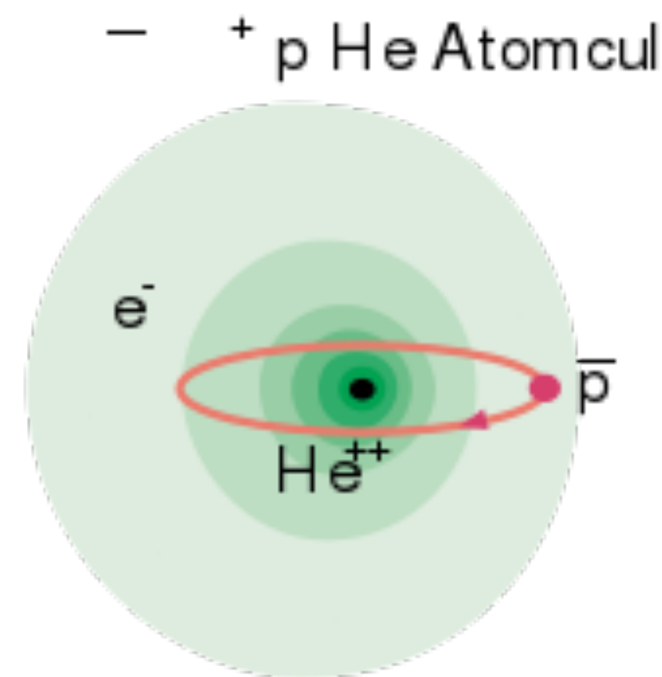
PSAS'2016

International Conference on Precision Physics of Simple Atomic Systems

Antiprotonic helium

Short history

- 1991 - first observations of long living states (microseconds)
- 2009 - measurement of magnetic moment
- 2011 - resolving hyperfine structure
- 2016 - precise measurement of antiproton-to-electron mass ratio (inspiration for us)



Antiprotonic He levels

$$r_n = \frac{n^2\hbar^2}{Zke^2m}$$

Transition $(n, l) \rightarrow (n', l')$	Experiment frequency (MHz)	Theor. frequency (MHz)	κ_M (ppb)	κ_Q (ppb)
$\bar{p}^4He^+$				
(40, 35) → (39, 34)	445608573(5)(4)(1)	445608572.3(4)	1.9	3.1
(38, 35) → (39, 34)	356155990.1(2.1)(2.0)(0.8)	356155990.5(4)	2.7	4.1
(39, 35) → (38, 34)	501948753.4(2.1)(1.9)(0.8)	501948755.1(2)	1.8	3.0
(37, 35) → (38, 34)	412885133.1(1.0)(0.8)(0.6)	412885132.4(2)	2.6	4.0
(37, 34) → (36, 33)	636878154.3(2.2)(1.9)(1.1)	636878152.09(5)	1.6	2.8
(34, 33) → (35, 32)	655062100(10)(10)(1)	655062101.92(7)	2.1	3.4
(35, 33) → (34, 32)	804633058.2(2.1)(1.8)(1.2)	804633058.46(6)	1.5	2.6
(32, 31) → (31, 30)	1132609226.7(2.8)(2.5)(1.4)	1132609224.01(8)	1.3	2.4
$\bar{p}^3He^+$				
(38, 34) → (37, 33)	505222282(4)(4)(1)	505222281.0(3)	1.8	3.1
(36, 34) → (37, 33)	414147510.4(2.6)(2.3)(1.2)	414147508.9(3)	2.6	4.0
(36, 33) → (35, 32)	646180416(5)(4)(1)	646180412.58(5)	1.6	2.8
(34, 32) → (33, 31)	822809167(5)(5)(1)	822809172.30(7)	1.5	2.6
(32, 31) → (31, 30)	1043128581(5)(4)(1)	1043128580.64(8)	1.3	2.5

M. Hori et.al., *Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to–electron mass ratio*, Science **354**, 610 (2016)

(37,35) state

In general, variational method is used to obtain ground states. In this case it would be (1,0)

We may postulate test wavefunctions with fixed angular momentum l=35

For these test wavefunctions, (36,35) is a ground state

We still need to find a way to get (37,35) state

(37,35) state

We use the variational principle
in space of l=35 test wavefunctions

We get an approximated
wavefunction for (36,35) state

We build a space of l=35 test wavefunctions
orthogonal to the (36,35) state

We use the variational principle in the new space
to find the lowest state - it will be (37,35)

(37,35) state

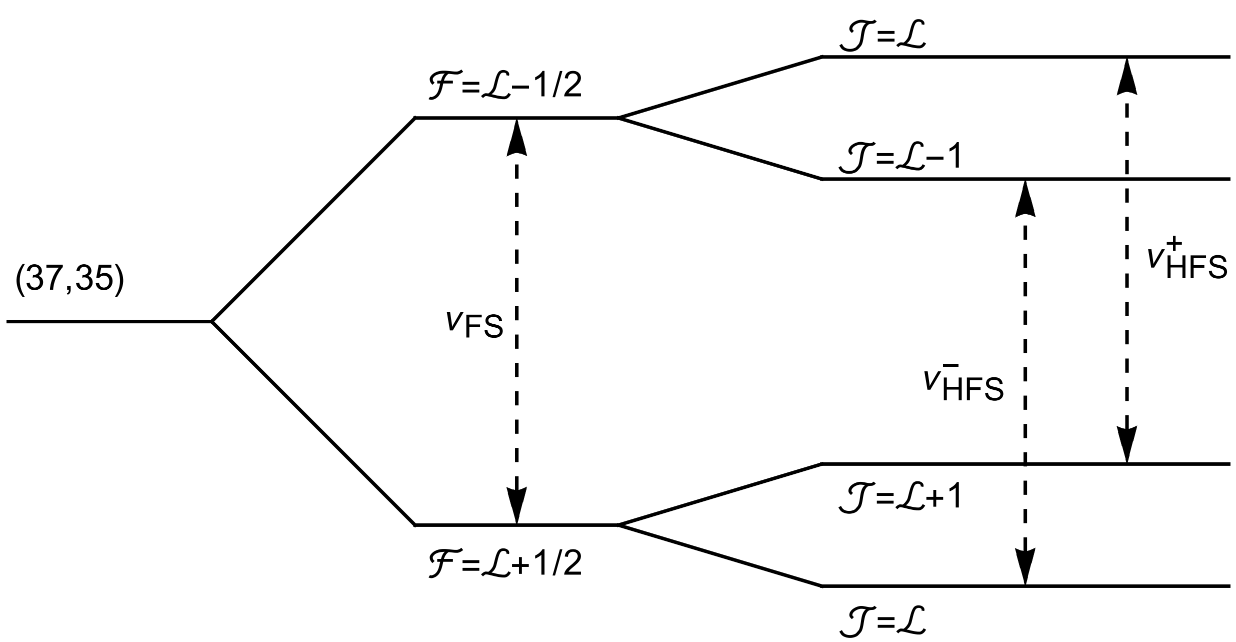
Variational principle works flawlessly for the first excited state only, if we know the precise wave function for the ground state.

(n, l)	This paper	Ref. [12]
$(36, 35)$	-2.979	-2.984
$(37, 35)$	-2.883	-2.899

[12] T. Yamazaki et.al., *Antiprotonic helium*, Physics Reports 366 (2002) 183–329

We also check: if our wavefunction was a little bit wrong, how much would it change our final results?

Hyperfine structure



$$\mathcal{J} = (\mathcal{L} + s_e) + s_{\overline{p}}$$

	ν^+_{HF} (GHz)	ν^-_{HF} (GHz)
This work	12.896 641(63)	12.924 461(63)
2002 [12]	12.895 96(34)	12.924 67(29)
Korobov [15]	12.8963(13)	12.9242(13)
Kino [17]	12.8960(13)	12.9239(13)

T. Pask, et.al., *Antiproton magnetic moment determined from the HFS of* pHe⁺,
Phys. Lett. B 678, 55 (2009)

Results

	Experiment [2]	Theory [51]	Difference	ΔE (at 90% C.L.)
ν^{+}_{HFS}	12.896 641(63) GHz	12.8963(13) GHz	0.3(1.3) MHz	2.2 MHz
ν^{-}_{HFS}	12.924 461(63) GHz	12.9242(13) GHz	0.3(1.3) MHz	2.2 MHz

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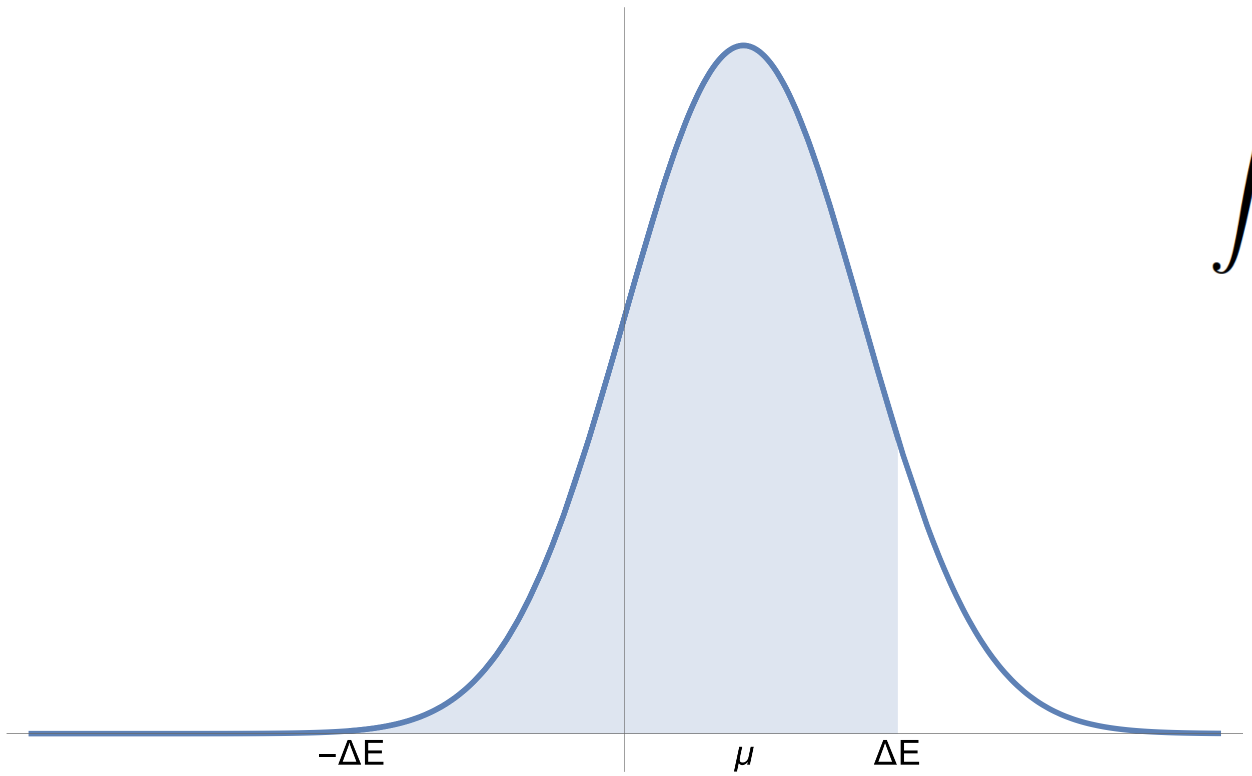
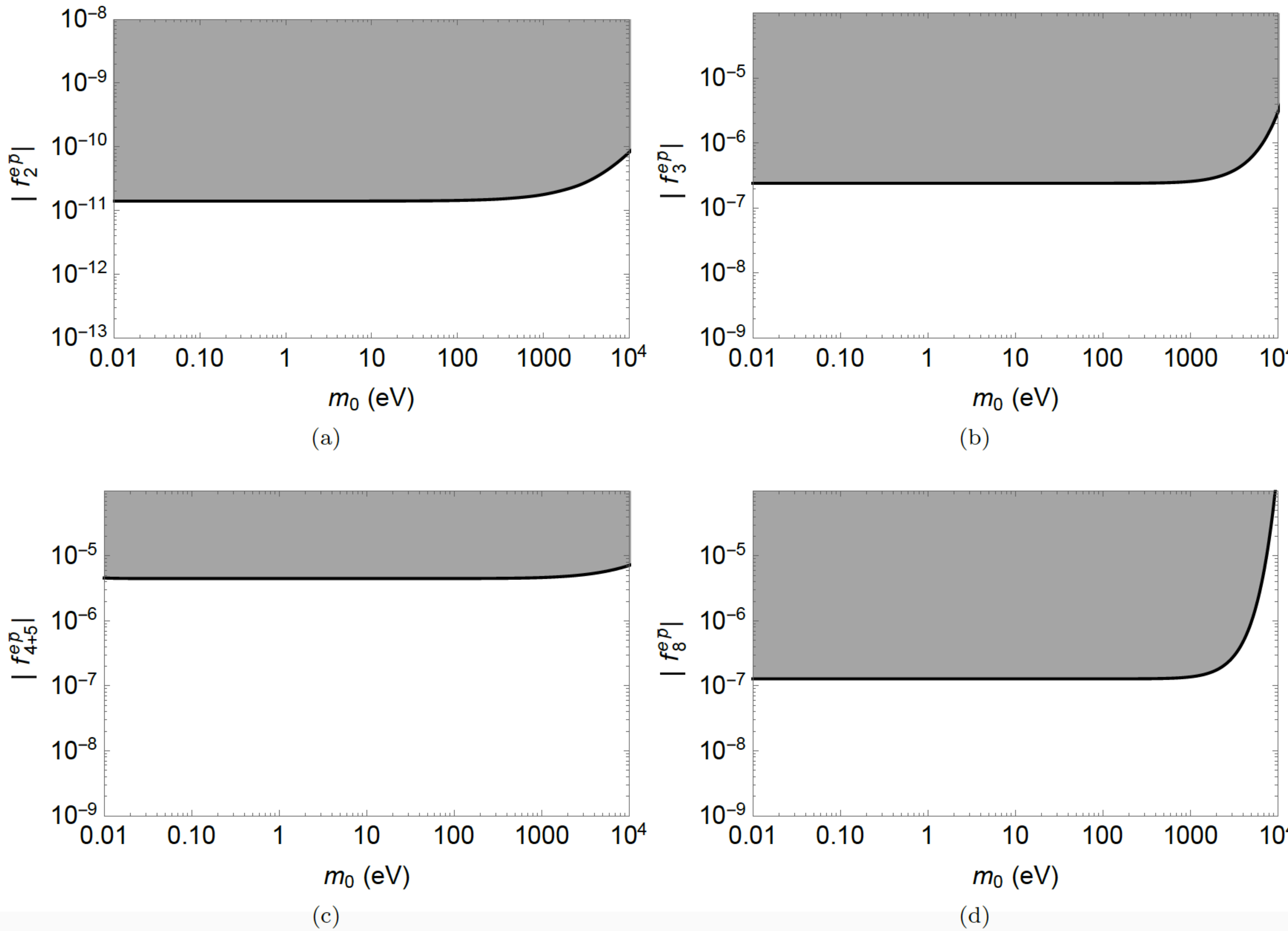


$$\int_{-\Delta E}^{+\Delta E} \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/(2\sigma^2)} dx = 0.9$$

Results



$|f_2^{e\bar{p}}|$
$|f_3^{e\bar{p}}|$
$|f_{4+5}^{e\bar{p}}|$
$|f_8^{e\bar{p}}|$
m_0 (eV)
0.01
0.10
1
10
100
1000
10^4
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-5}
10^{-6}
10^{-7}
(a)
(b)
(c)
(d)

Results

	$\lvert f_2 \rvert$	$\lvert f_3 \rvert$	$\lvert f_{4+5} \rvert$	$\lvert f_8 \rvert$
Estimates	3×10^{-12}	3×10^{-8}	2×10^{-6}	3×10^{-8}
Numerics	1.4×10^{-11}	2.5×10^{-7}	4.4×10^{-6}	1.3×10^{-7}

Summary

- First constraints on semileptonic spin-dependent interactions between matter and antimatter
- First constraints on non-static spin-dependent interactions between matter and antimatter
- Proof that we can easily obtain constraints on exotic interactions using various atomic systems

Thank you for your attention

- F. Ficek, et.al., *Constraints on exotic spin-dependent interactions between matter and antimatter from antiprotonic helium spectroscopy*, Phys. Rev. Lett. **120**, 183002 (2018)
- M. Hori et.al., *Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to–electron mass ratio*, Science **354**, 610 (2016)
- T. Pask, et.al., *Antiproton magnetic moment determined from the HFS of* $\bar{p}He^+$, Phys. Lett. B **678**, 55 (2009)
- T. Yamazaki et.al., *Antiprotonic helium*, Physics Reports **366** (2002), 183–329