Laboratoire Kastler Brossel
Physique quantique et applications

Testing Bound-state Quantum electrodynamics with muonic and antiprotonic atoms

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Solvay workshop, November 24-27, 2019
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Outline

- QED contributions in normal and exotic atoms
- Status of comparison between theory and experiment for highly-charged ions
- The proton size puzzle
- Testing QED in an other framework
    - Muonic Atoms: measuring nuclear size or QED effects?
    - Antiprotonic atoms: nuclear size, strong interaction or QED?
- Conclusion

Why testing QED (and beyond!)?

- Often asked question: the electromagnetic interaction is well understood, so what is left to test in QED?
  - It is the model for quantum field theory
  - the series of bound state QED corrections has a radius of convergence equal to zero (F. J. Dyson, Phys. Rev. 85, 631 (1952).)
  - not obvious how orders beyond 2 behave… (should be convergent up to n=137 but…)
  - QED corrections to multi-electrons systems impossible to obtain with required accuracy and consistent order
  - we can measure very accurately, and possibly be sensitive to effects beyond the standard model
  - need to understand QED to make better predictions, e.g., for super-heavy elements

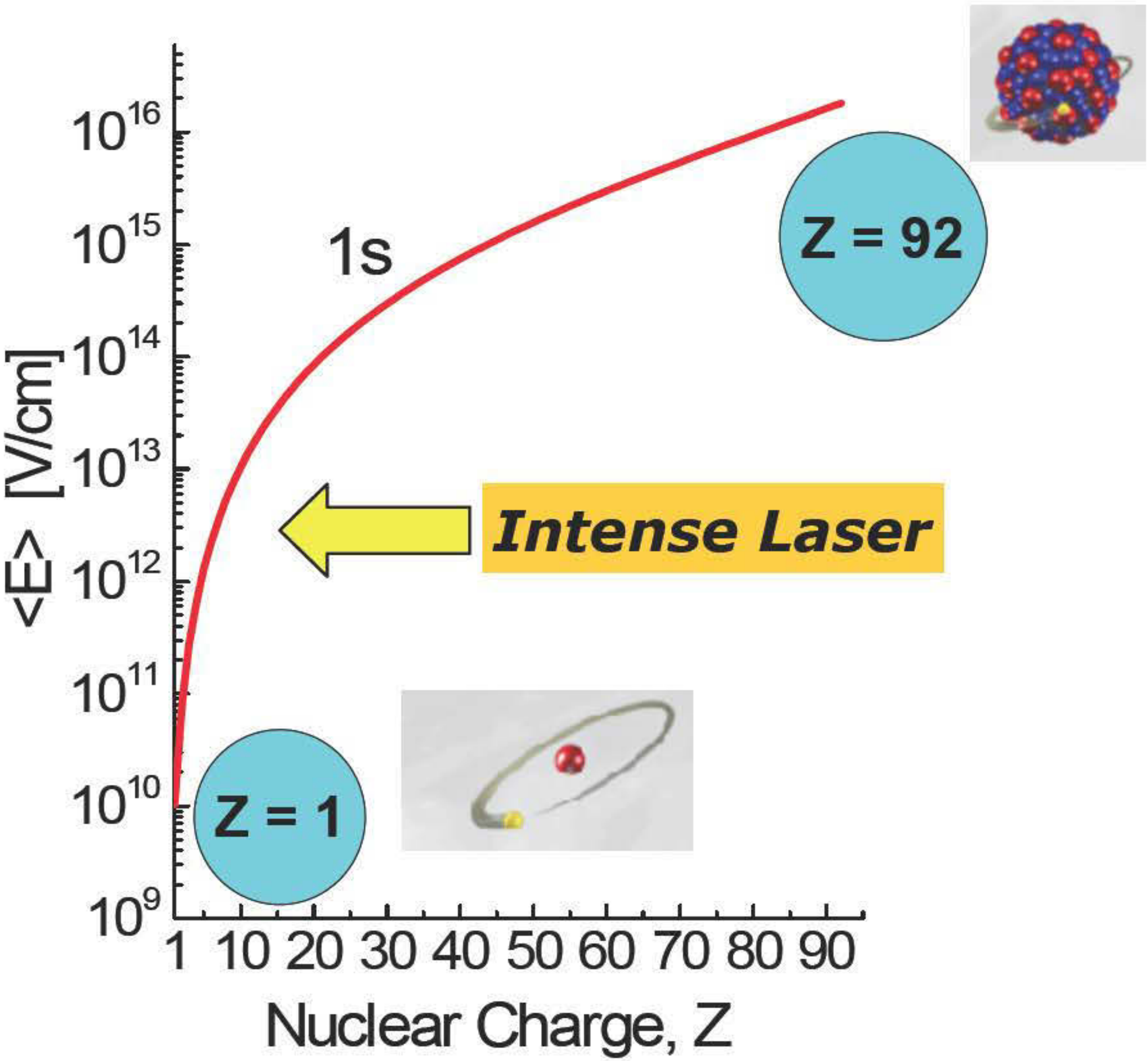
Why testing QED (and beyond!)?

- Often asked question: the electromagnetic interaction is well understood, so what is left to test in QED?
  - understand atoms in super-critical field (U^{92+} on U collisions for example $Z_1+Z_2>173$)
  - distinguish nuclear and QED contributions (either to measure nuclear properties or to measure atomic properties)
  - low-energy tests of strong interaction or particle and anti-particle interaction
  - fundamental constant drifts…
  - better atomic clocks using highly-charge ions (insensitive to black-body radiation…)
  - …

Atomic energies

All order Dirac+Vacuum polarization treatment+other QED

Atomic Physics in Strong Coulomb Fields



H-like Uranium
E_K = -132 • 10^3 eV
<E>= 1.8 • 10^{16} V/cm

Hydrogen
E_K = -13.6 eV
<E>= 1 • 10^{10} V/cm

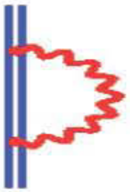
One electron BSQED corrections

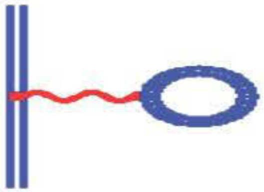
successive orders for QED

one electron QED at order α

Self Energy

$\frac{\alpha}{\pi}$





Vacuum Polarization

H-like "One Photon" order (α/π)

Many calculations, very accurate down to Z=1

$$\Delta E_{SE} = \frac{\alpha}{\pi}\frac{(Z\alpha)^4}{n^3}F(Z\alpha).$$

$$\frac{\alpha}{\pi} = 2.3 \times 10^{-3}$$

$$E_{NR} = \frac{(Z\alpha)^2}{n^2}$$

Content of a Feynman diagram: Self-energy

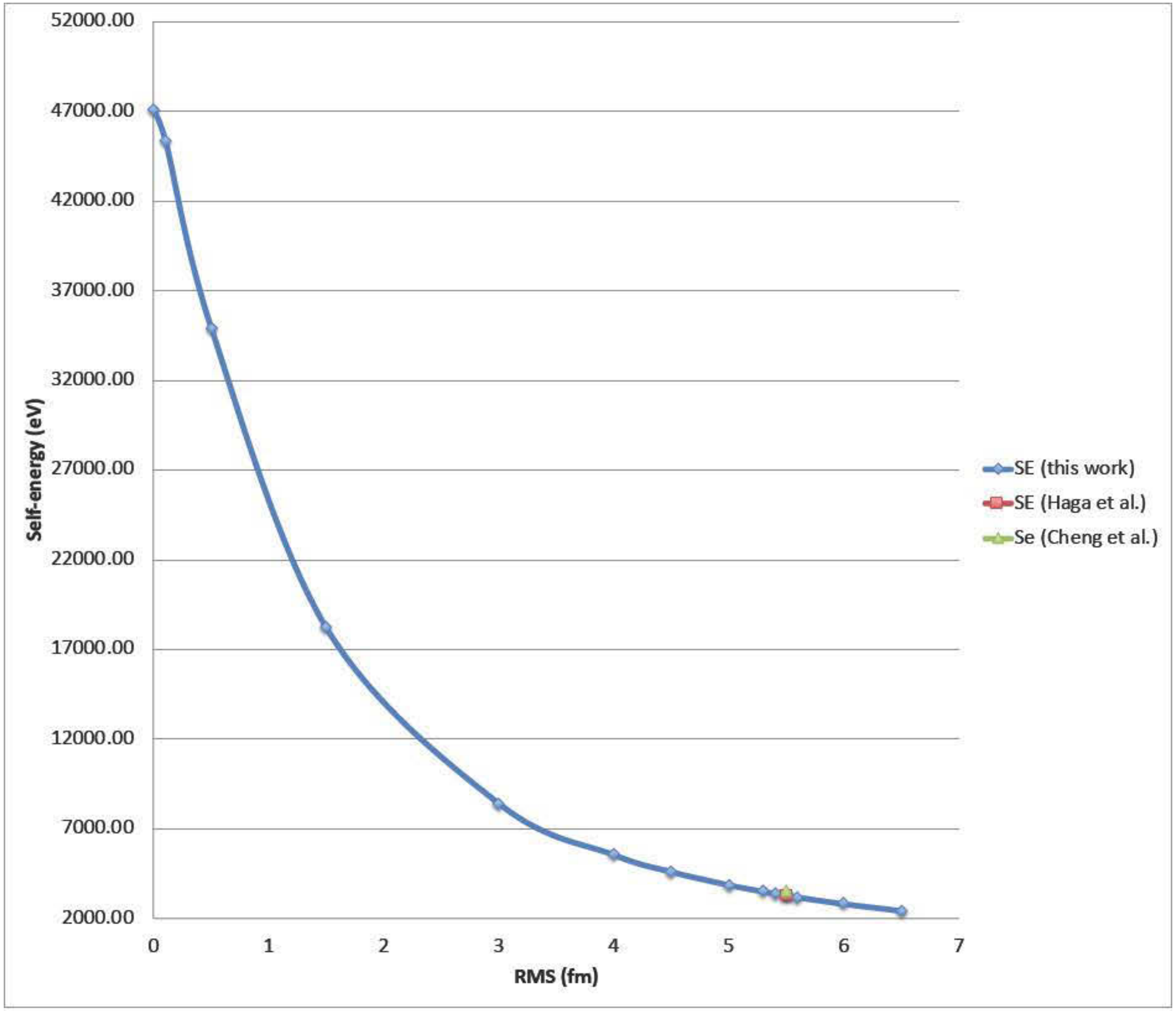
- Self-energy
  - A bound electron emit and and reabsorb a photon.

- Finite nuclear size contribution ditticult to evaluate for heavy particles (muon, $\bar{p}$ in deep bound states)

No potential

$$\Delta E_n = -i\pi\alpha \int d(t_2 - t_1)\, d^3\mathbf{x}_2\, d^3\mathbf{x}_1\, \boxed{\bar{\psi}_n(x_2)}\, \gamma_\mu S_F{}^e(x_2\,,\, x_1)\, \gamma^\mu \boxed{\psi_n(x_1)}$$
$$\times\, D_F(x_2 - x_1) - \delta m \int d^3\mathbf{x}\, \bar{\psi}_n(x)\, \psi_n(x),$$

Strong nuclear size effects on QED: ex Self-Energy

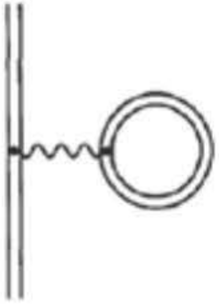


With Peter Mohr (NIST)

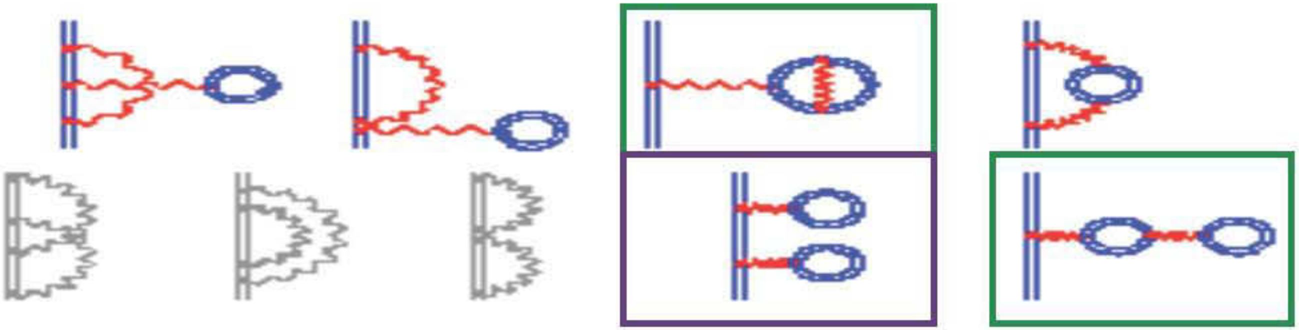
Content of a Feynman diagram: vacuum polarization

- Vacuum polarization
  - The electron interact with a virtual electron-positron (or muon-antimuon) pair in the field of the nucleus

$$E_{\mathrm{VP}}^{(2)} = 4\pi i\alpha \int d(t_2 - t_1) \int d\boldsymbol{x}_2 \int d\boldsymbol{x}_1\, D_{\mathrm{F}}(x_2 - x_1) \times \mathrm{Tr}[\gamma_\mu S_{\mathrm{F}}(x_2, x_2)] \boxed{\overline{\phi}_n(x_1)\gamma^\mu \phi_n(x_1)} \longrightarrow \text{Potential}$$



one electron QED at order α^2



H-like “Two Photon” order $(\alpha/\pi)^2$

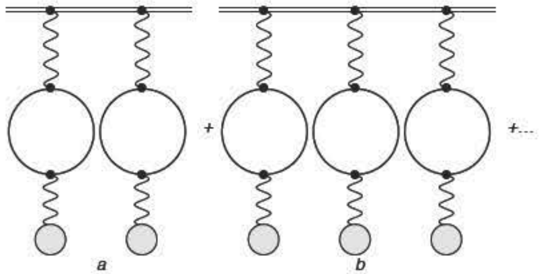
Loop after loop
VP in Dirac Eq.

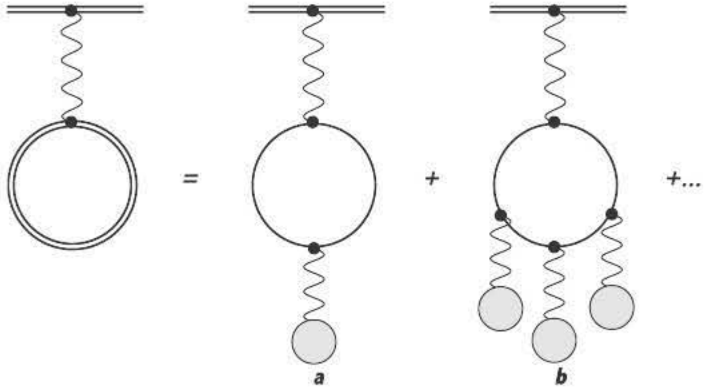
Källèn & Sabry
Potential

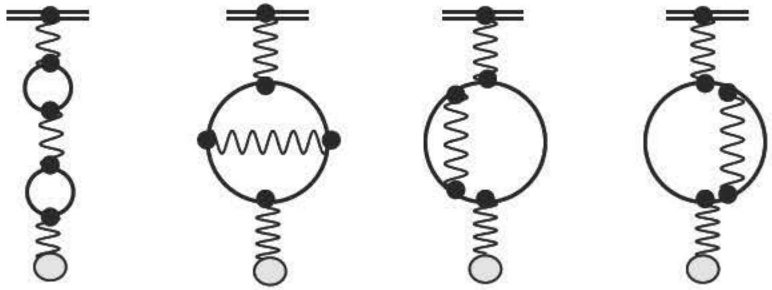
Others not precisely known for exotic atoms

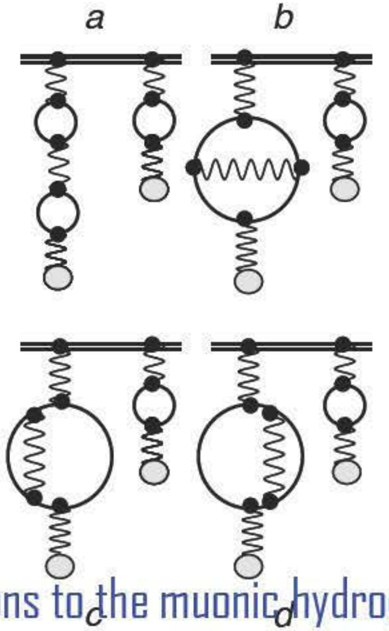
Contributions included to all-order

All-order: the charge distribution is included exactly in the wavefunction and in the operator, when relevant. Higher order Vacuum Polarization contribution included by numerical solution of the Dirac equation







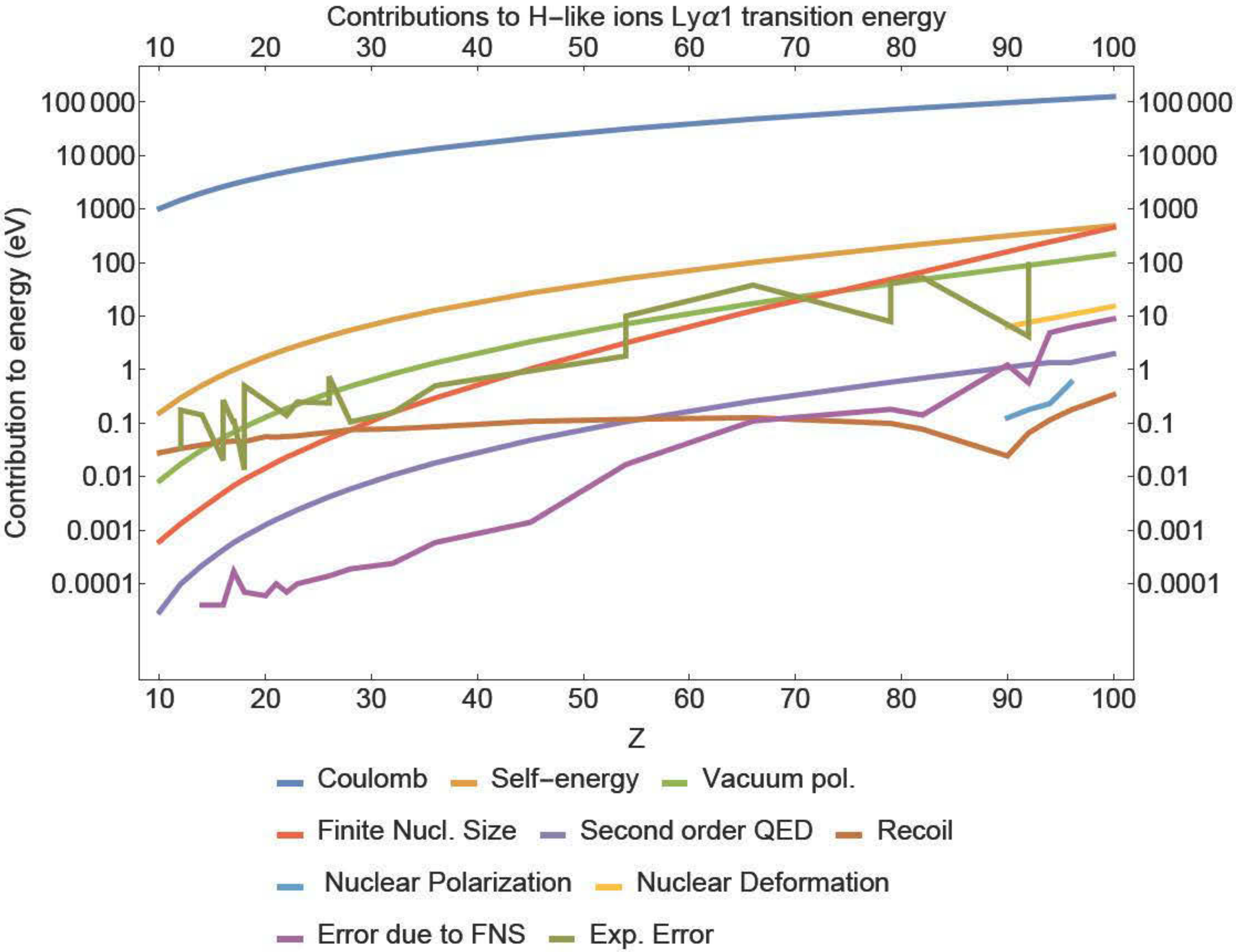


Nonperturbative evaluation of some QED contributions to the muonic hydrogen n=2 Lamb shift and hyperfine structure, P. Indelicato. Phys. Rev. A **87,** 022501 (2013).

The size of QED effects

in normal atoms and ions

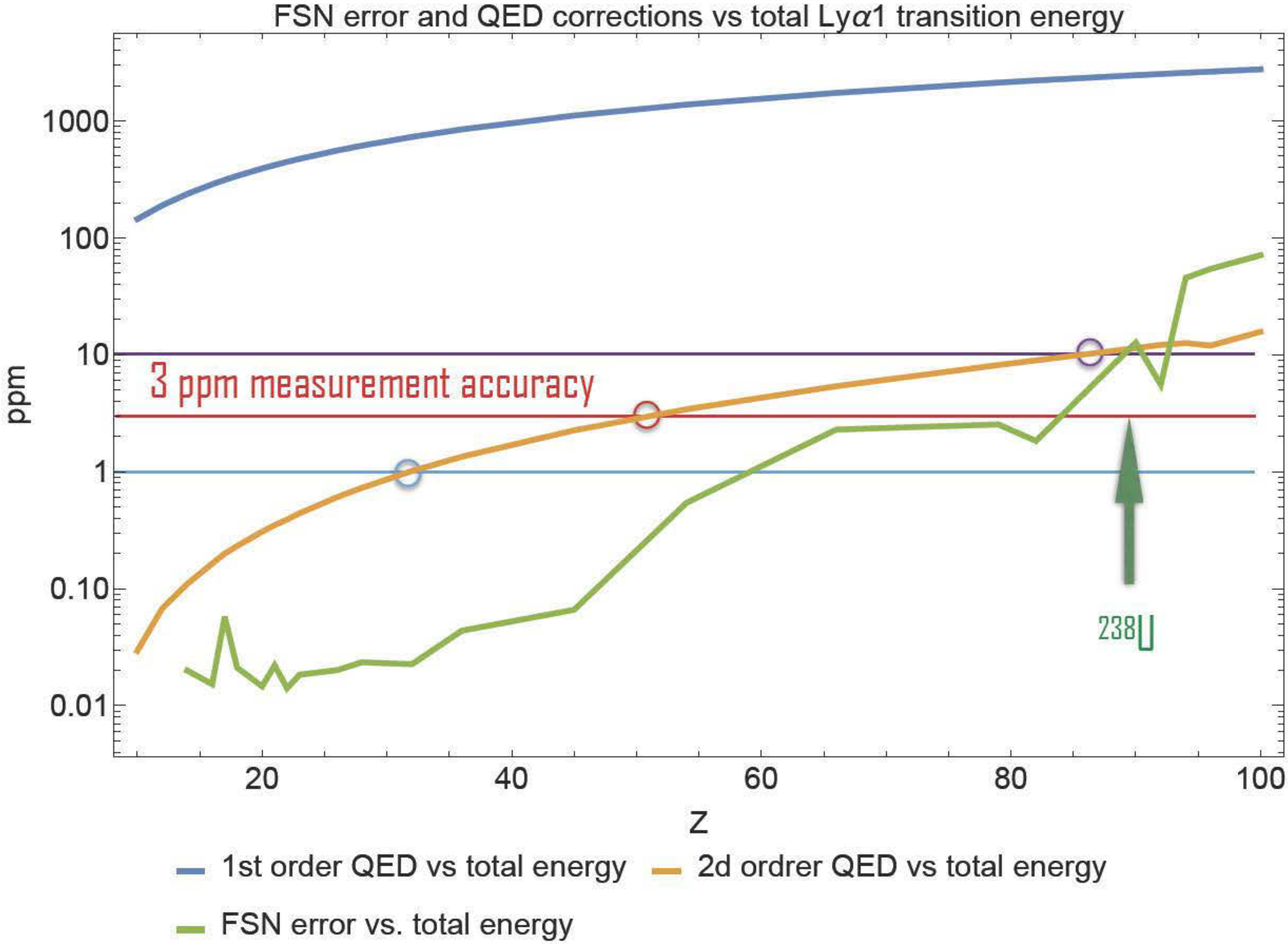
What are we testing?



Where to do measurement to best test QED

Nuclear effects and QED tests on H-like ions

Is there an optimal Z to avoid nuclear uncertainties?



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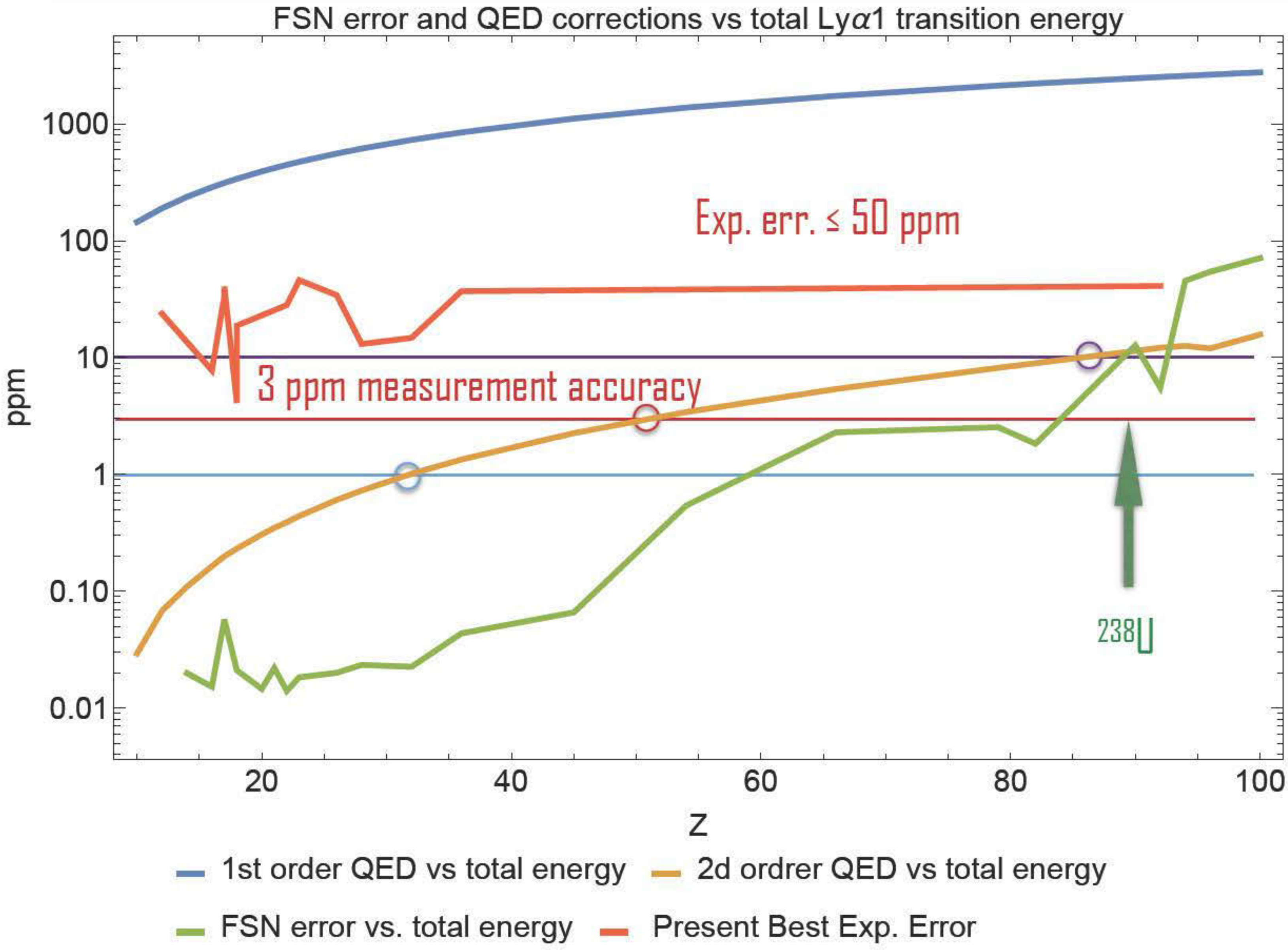
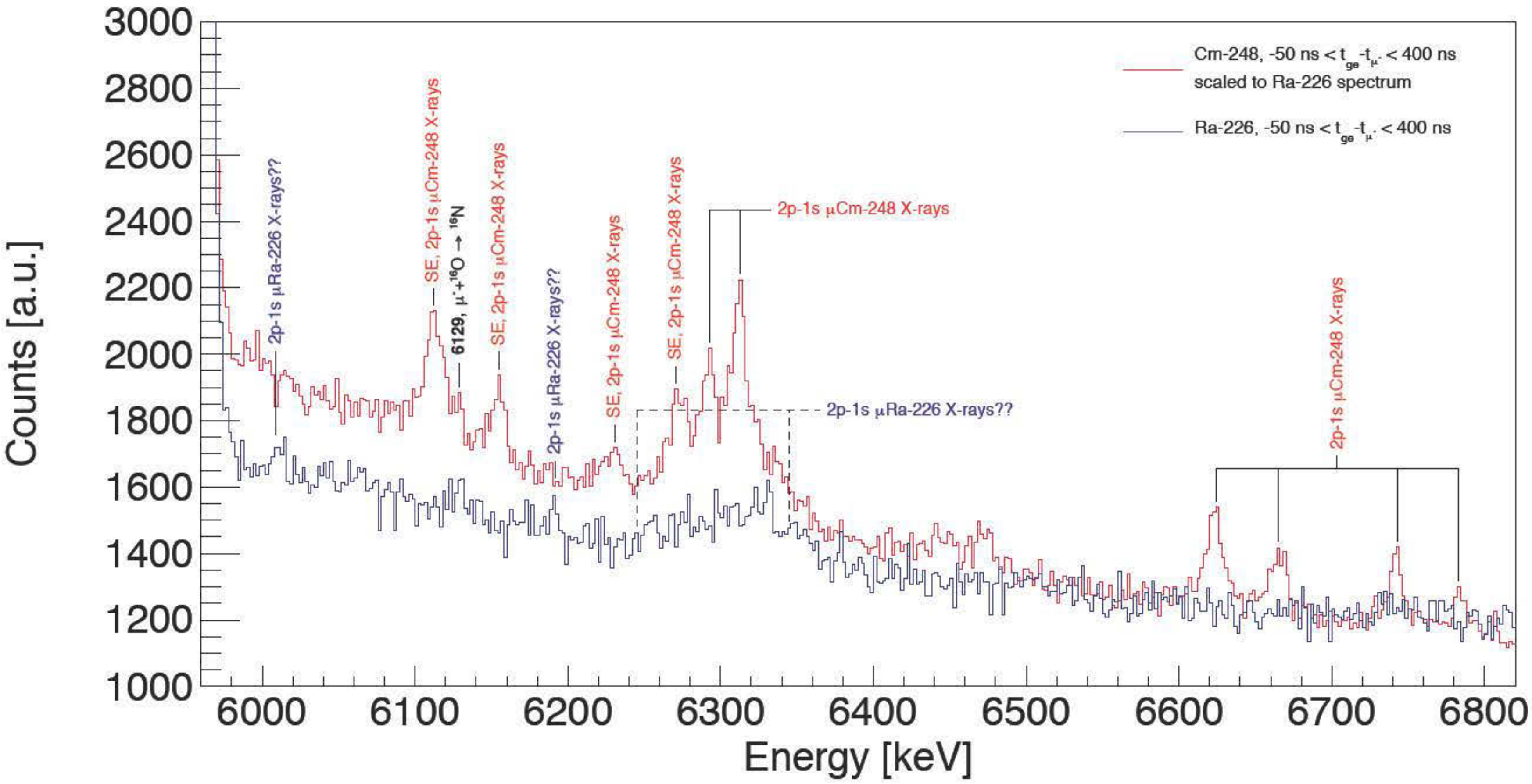


Other ways to test BSQED?

what about exotic atoms?

exotic atoms?



μX experiment at PSI

Viewed as a good way to measure nuclear parameters because 207 times closer to the nucleus

The proton and deuteron size puzzle

An example of the different effects for the lightest element

8 juillet 2010

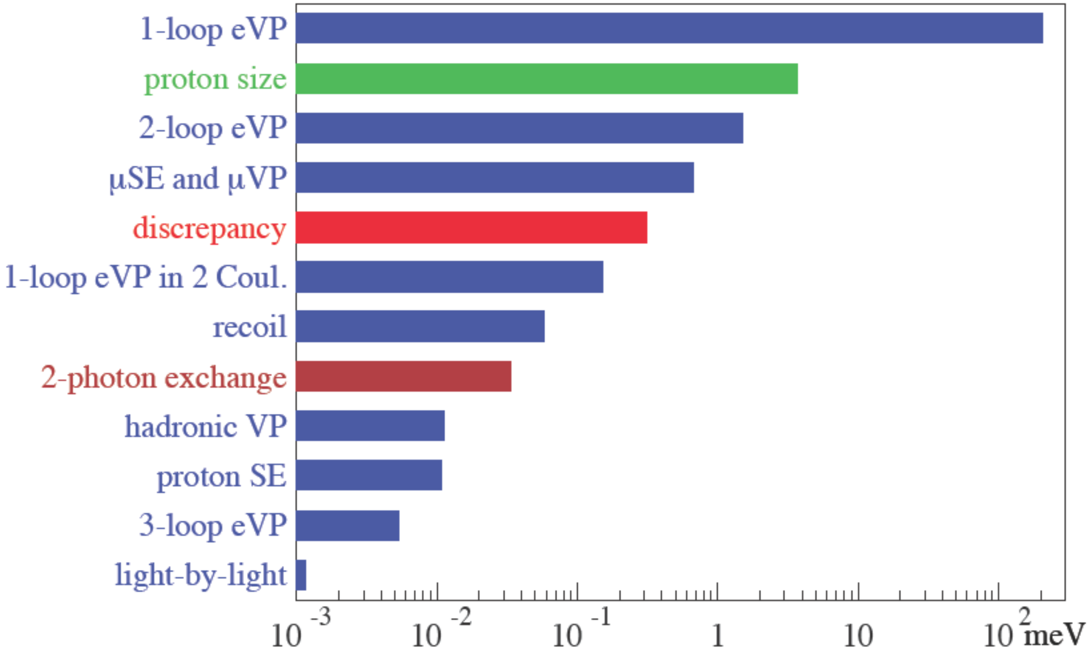
The size of the proton, R. Pohl, A. Antognini, F. Nez *et al.* Nature **466,** 213-216 (2010).

Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen, A. Antognini, F. Nez, K. Schuhmann *et al.* Science **339,** 417-420 (2013).

μP theory

Discrepancy = 0.31 meV
Theory uncertainty = 0.0025 meV

$$\Delta E^{\mathrm{th}} = 206.0668(25) - 5.2275(10)\, r_{\mathrm{p}}^2 \quad [\mathrm{meV}]$$



Pachucki, PRA 60, 3593 (1999)

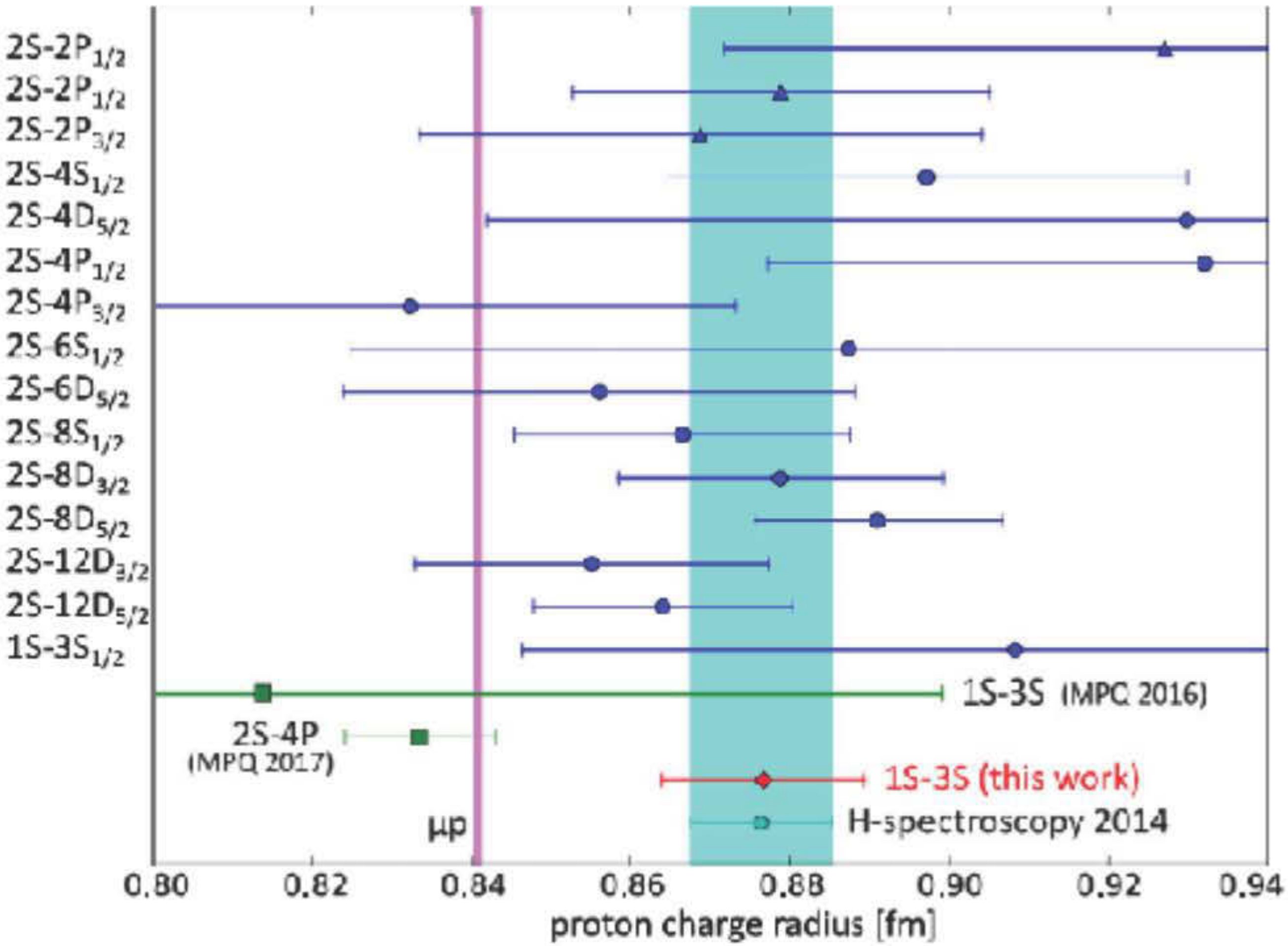
Borie, arXiv: 1103.1772-v7

Jentschura, Ann. Phys. 326, 500 (2011)

Karshenboim, J. Phys. Chem. Ref. Data 44, 031202 (2015)

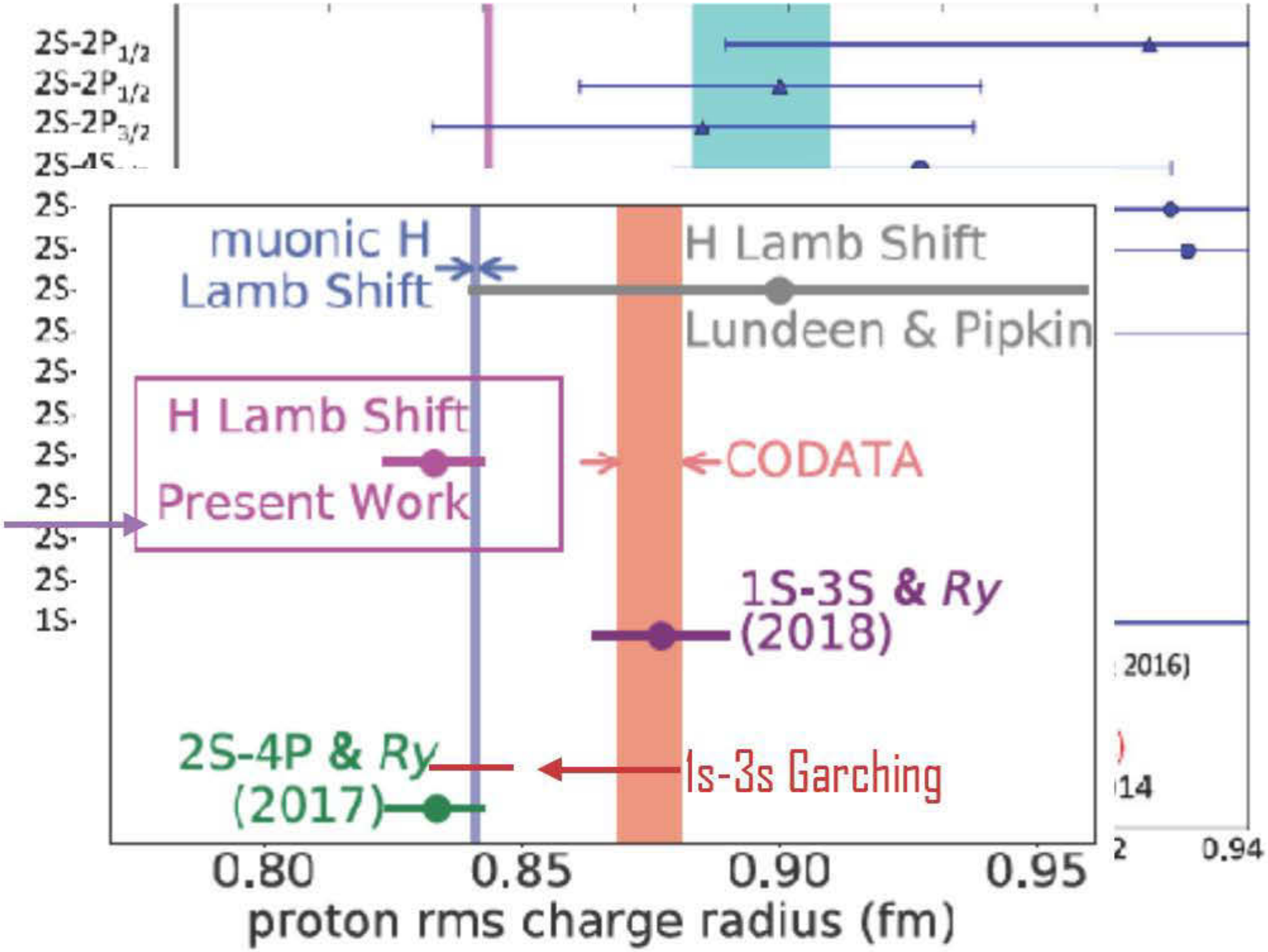
Indelicato, Martynenko, Miller, Eides, Pineda....

Proton charge radius (Fall 2019)



N. Bezginov, T. Valdez, M. Horbatsch, et al., Science 365, 1007 (2019).

Proton charge radius (Fall 2019)

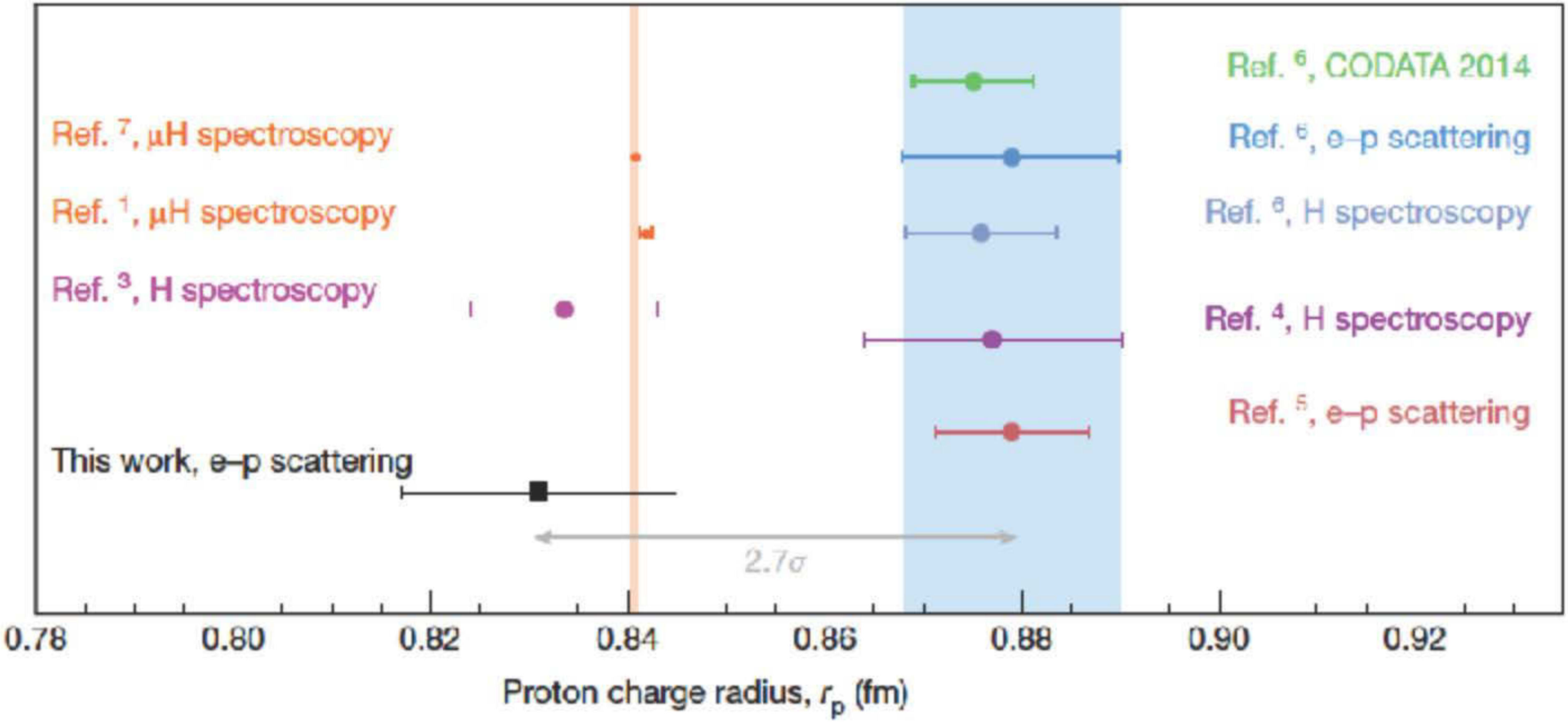


Hessels 2019

1s-3s Garching

N. Bezginov, T. Valdez, M. Horbatsch, et al., Science 365, 1007 (2019).

Proton charge radius (Fall 2019)



W. Xiong, A. Gasparian, H. Gao, et al., Nature 575, 147 (2019).

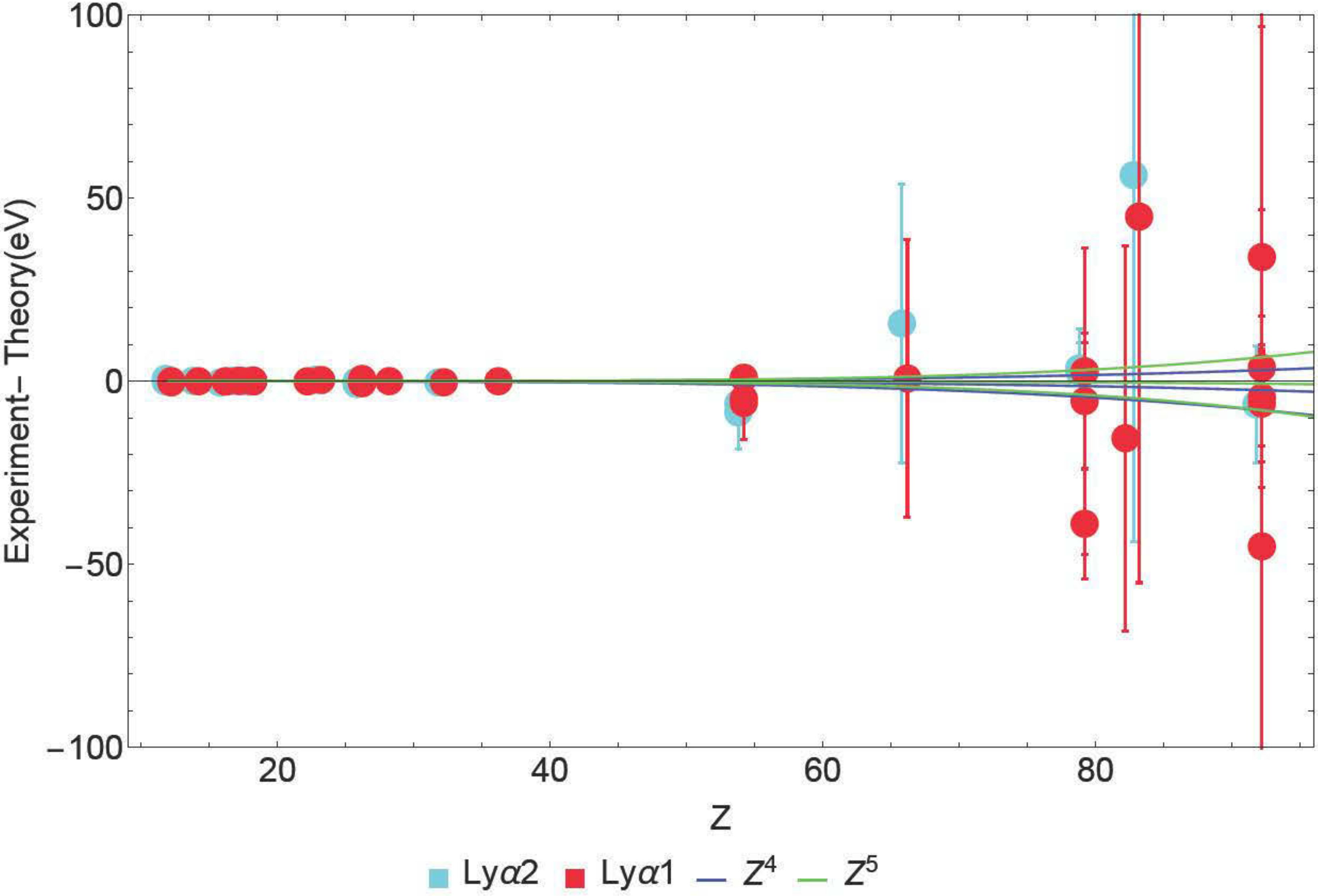
Comparison between theory and experiment

Few electron ions

Analysis for one-electron ions

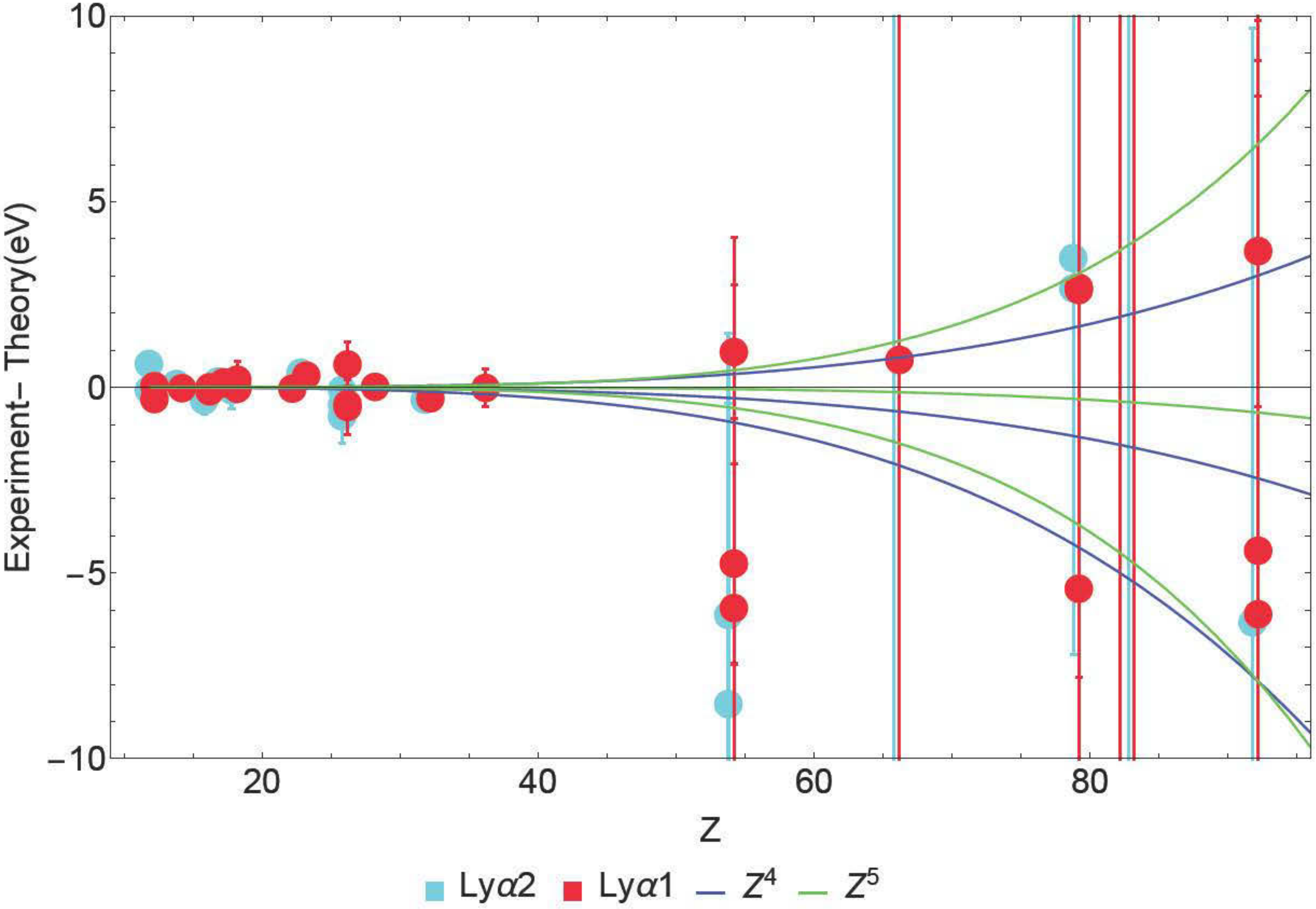
So far so good…

Comparison Theory-Experiment for H-like ions



P. Indelicato, Journal of Physics B: Atomic, Molecular and Optical Physics 52, 232001 (2019).

Comparison Theory-Experiment for H-like ions

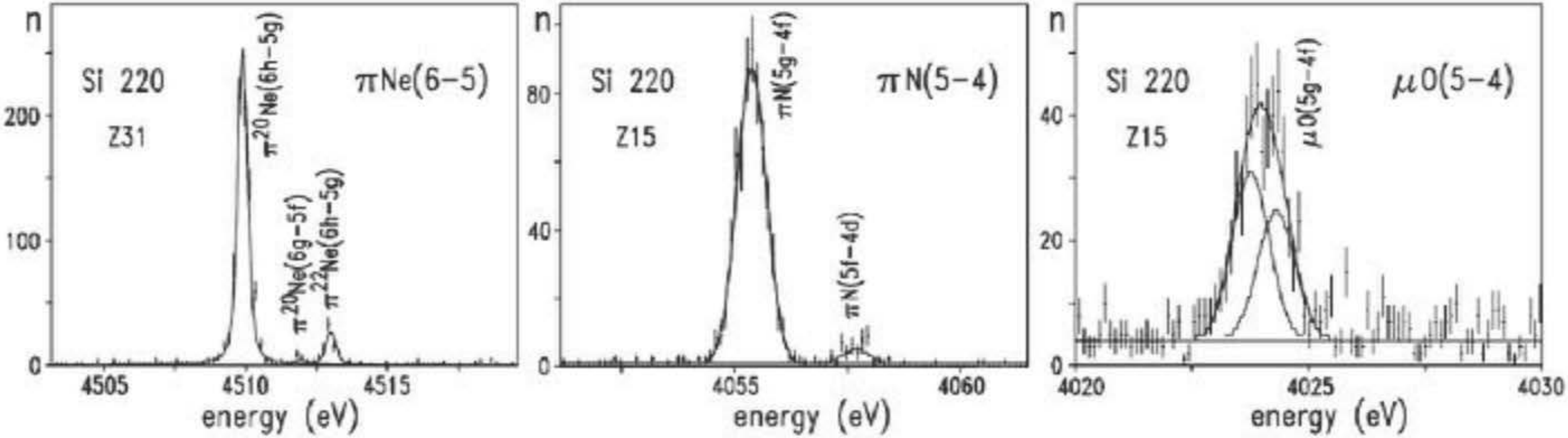


QED without nuclear effects?

Can one find muonic atoms and states to measure with high-resolution detectors

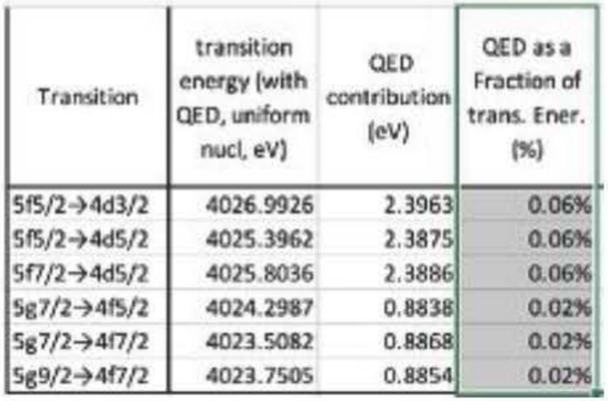
LKB

Measurements in a gaz with crystal spectrometer



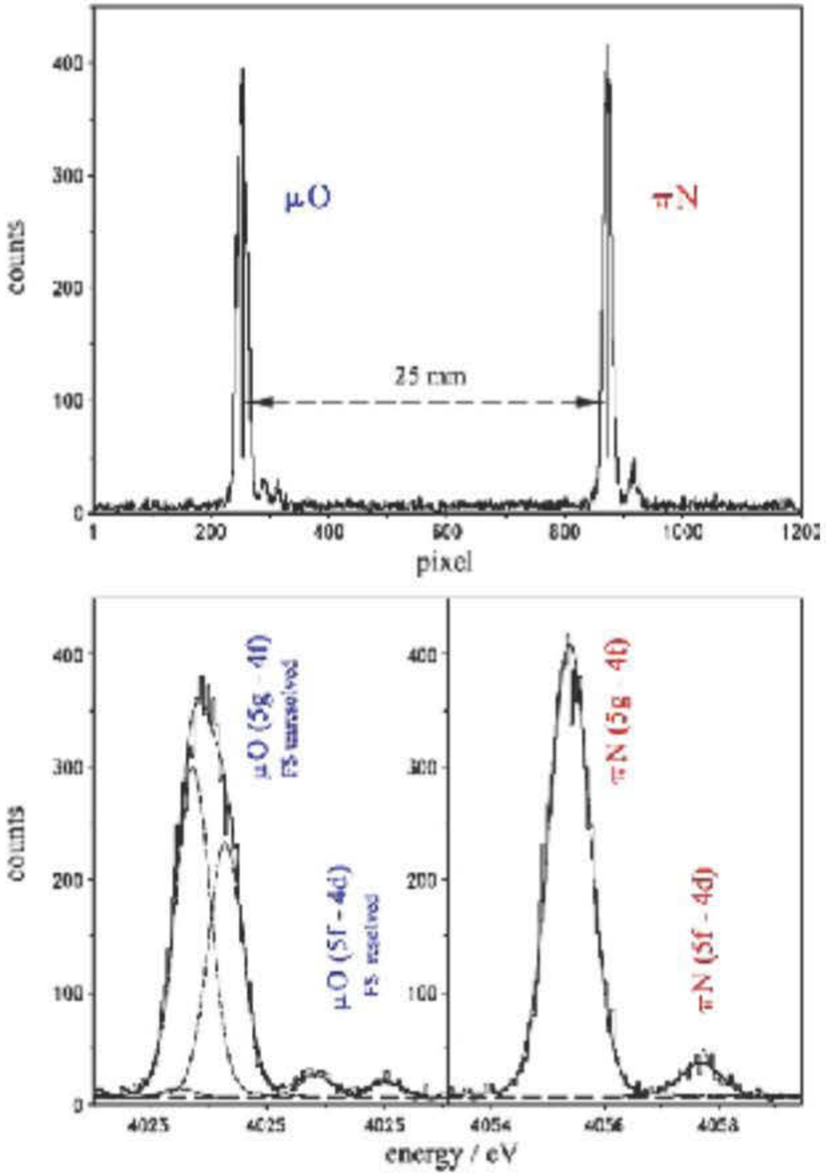
Siems, T., D. F. Anagnostopoulos, G. Borchert, D. Gotta, P. Hauser, K. Kirch, L. M. Simons, P. El-Khoury, P. Indelicato, M. Augsburger, D. Chatellard and J.-P. Egger (2000). "First direct observation of coulomb explosion during the formation of exotic atoms." Physical Review Letters **84**(20): 4573-4576.

used the cyclotron trap at PSI



Transition	transition energy (with QED, uniform nucl, eV)	QED contribution (eV)	QED as a Fraction of trans. Ener. (%)
5f5/2→4d3/2	4026.9926	2.3963	0.06%
5f5/2→4d5/2	4025.3962	2.3875	0.06%
5f7/2→4d5/2	4025.8036	2.3886	0.06%
5g7/2→4f5/2	4024.2987	0.8838	0.02%
5g7/2→4f7/2	4023.5082	0.8868	0.02%
5g9/2→4f7/2	4023.7505	0.8854	0.02%

Measurements in a gaz with crystal spectrometer



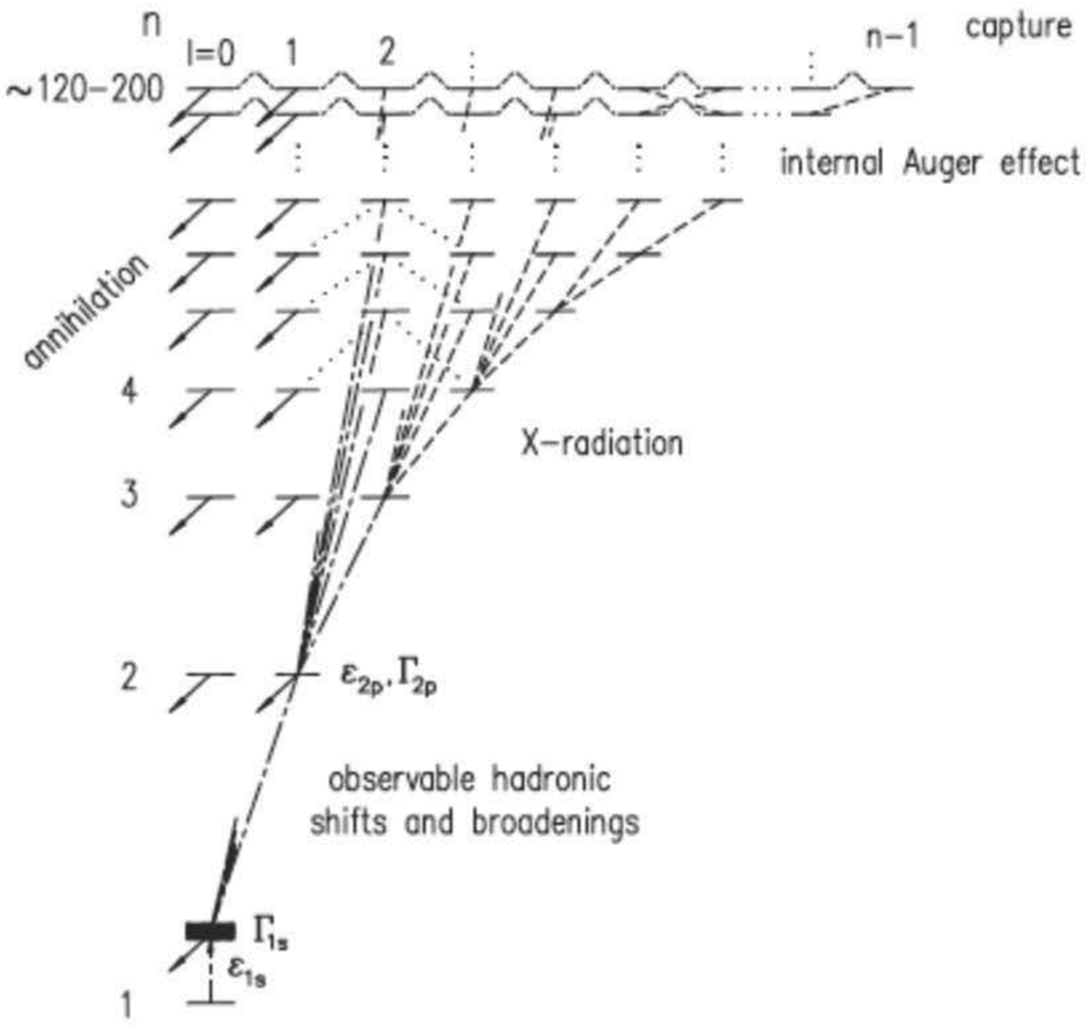
Trassinelli, M., D. F. Anagnostopoulos, G. Borchert, A. Dax, J. P. Egger, D. Gotta, M. Hennebach, P. Indelicato, Y. W. Liu, B. Manil, N. Nelms, L. M. Simons and A. Wells (2016). "Measurement of the charged pion mass using X-ray spectroscopy of exotic atoms." Physics Letters B 759: 583.

used the cyclotron trap at PSI

Using exotic atoms to test QED

Up to now used to measure nuclear parametersProgress in micro-calorimeters could help!

Exemple: rare gaz antiprotonic atoms x rays



Gotta, D., K. Rashid, B. Fricke, P. Indelicato and L. M. Simons (2008). "X-ray transitions from antiprotonic noble gases." The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics **47**(1): 11-26.

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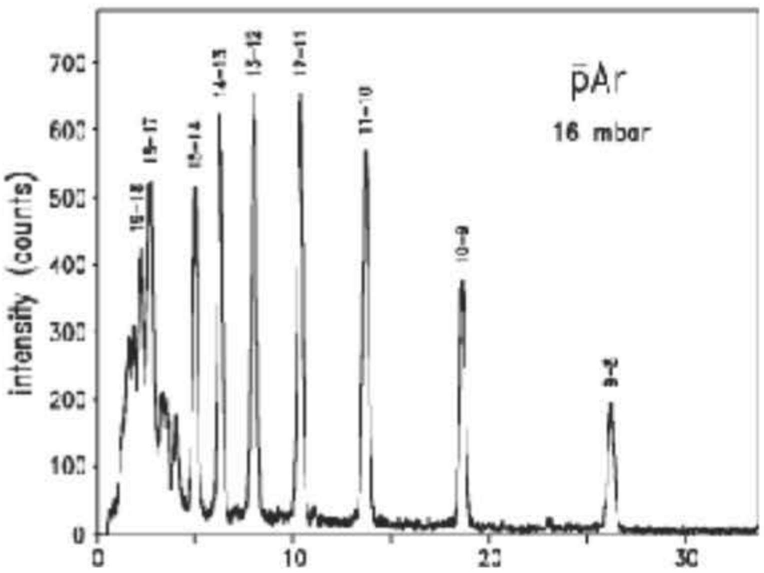
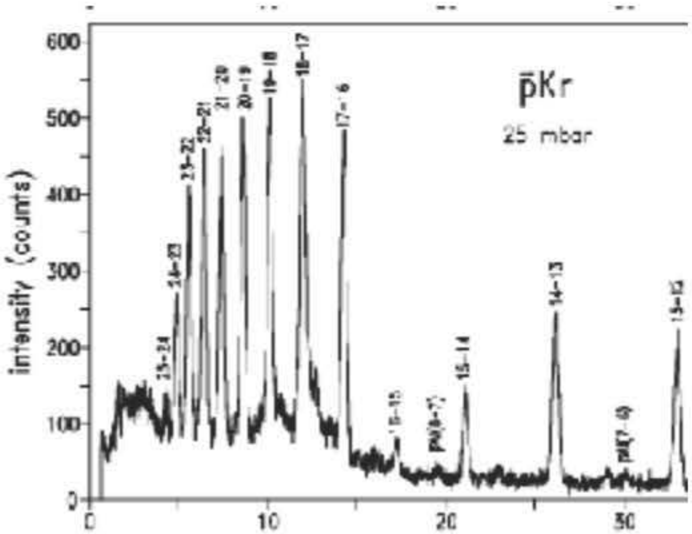
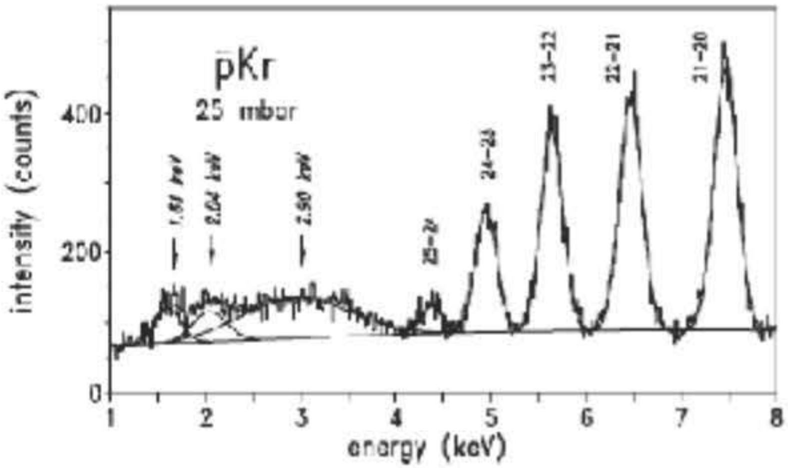
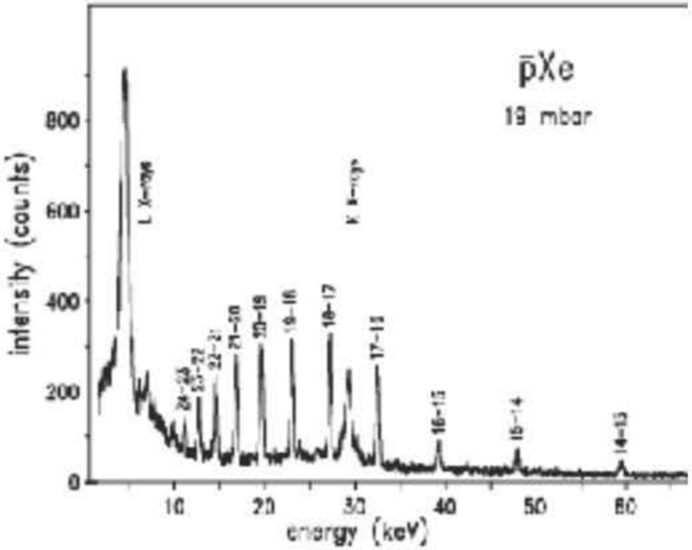






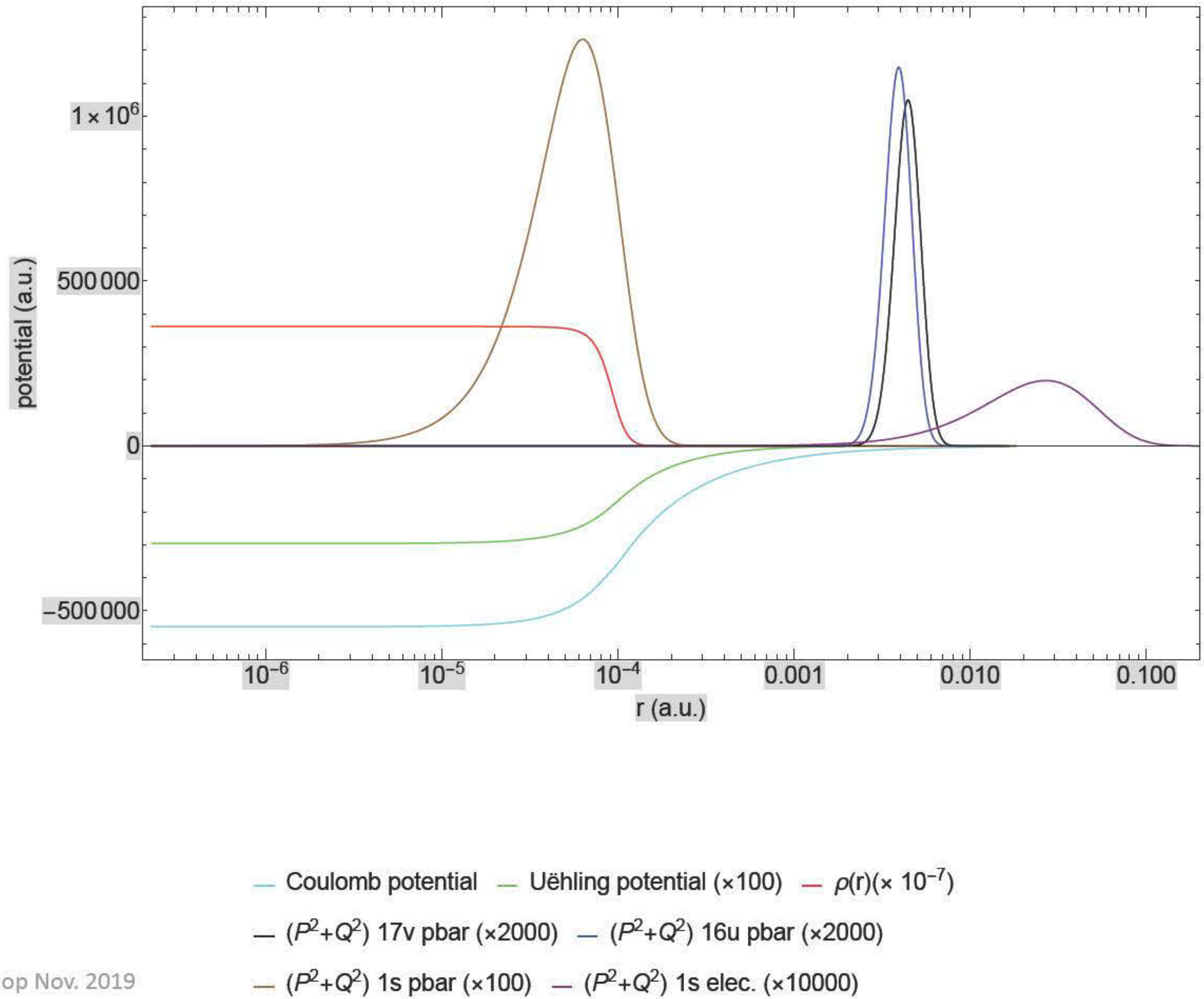


Gotta, D., K. Rashid, B. Fricke, P. Indelicato and L. M. Simons (2008). "X-ray transitions from antiprotonic noble gases." The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics **47**(1): 11-26.

Calculation

- Generate all possible E1, E2, M1, M2 transitions input data between levels, starting at n=30 as an example (60 initial levels, 900 in total, 41000 transitions)
- Use general MCDF code with exotic atoms capabilities to evaluate all transitions energies and probabilities
  - Vacuum polarization included in the Dirac Equation (re-summing all loop-after-loop diagrams)
  - Vacuum polarization in perturbation
  - point nucleus
- Calculate the QED and finite nuclear size (FNS) contribution to all transition energies
- extract results with large QED and small FNS correction
- add 2, 10, 18 electrons to see the shift due to remaining electrons, with full Dirac-Fock, Breit interaction…

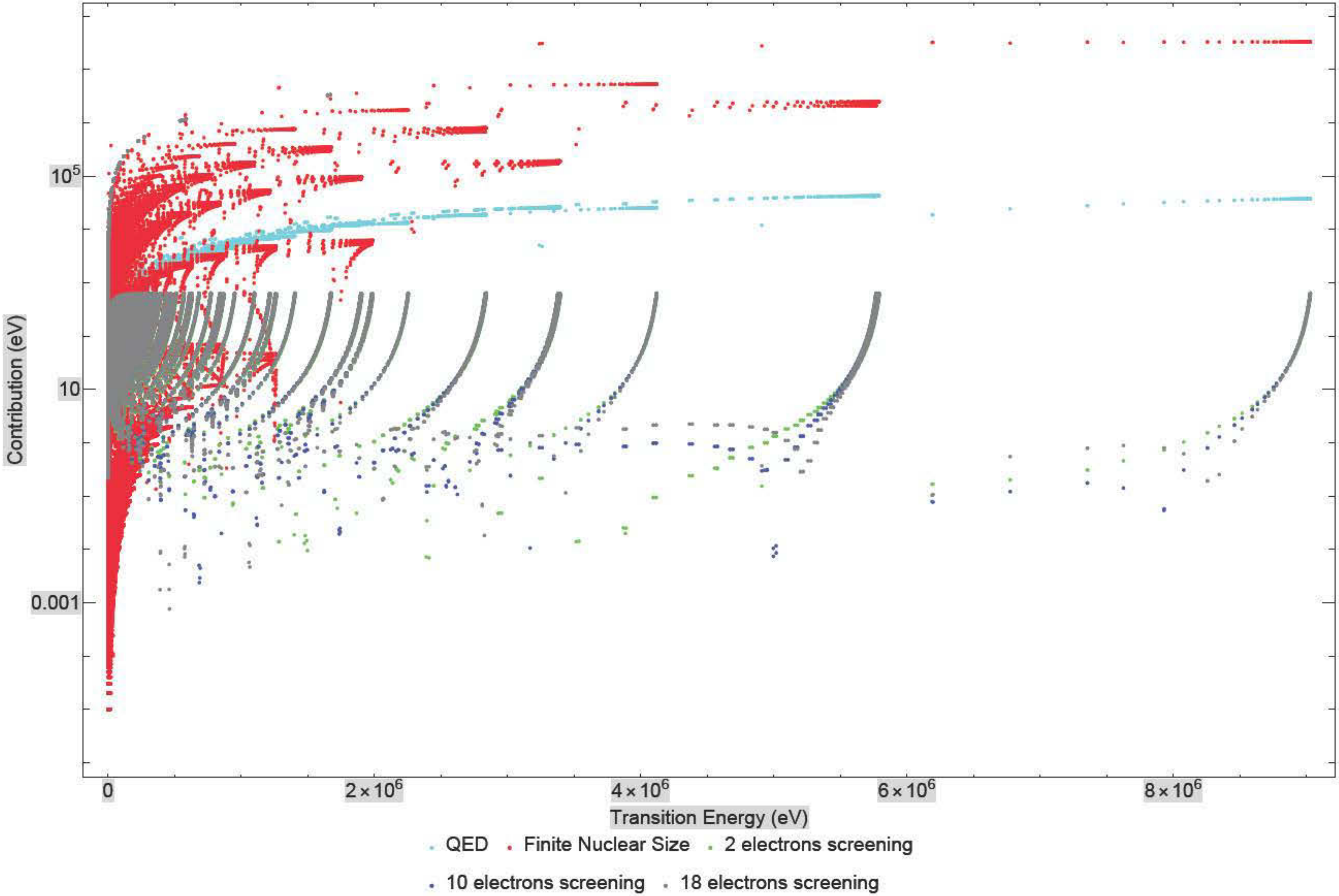
Wavefunctions and potentials



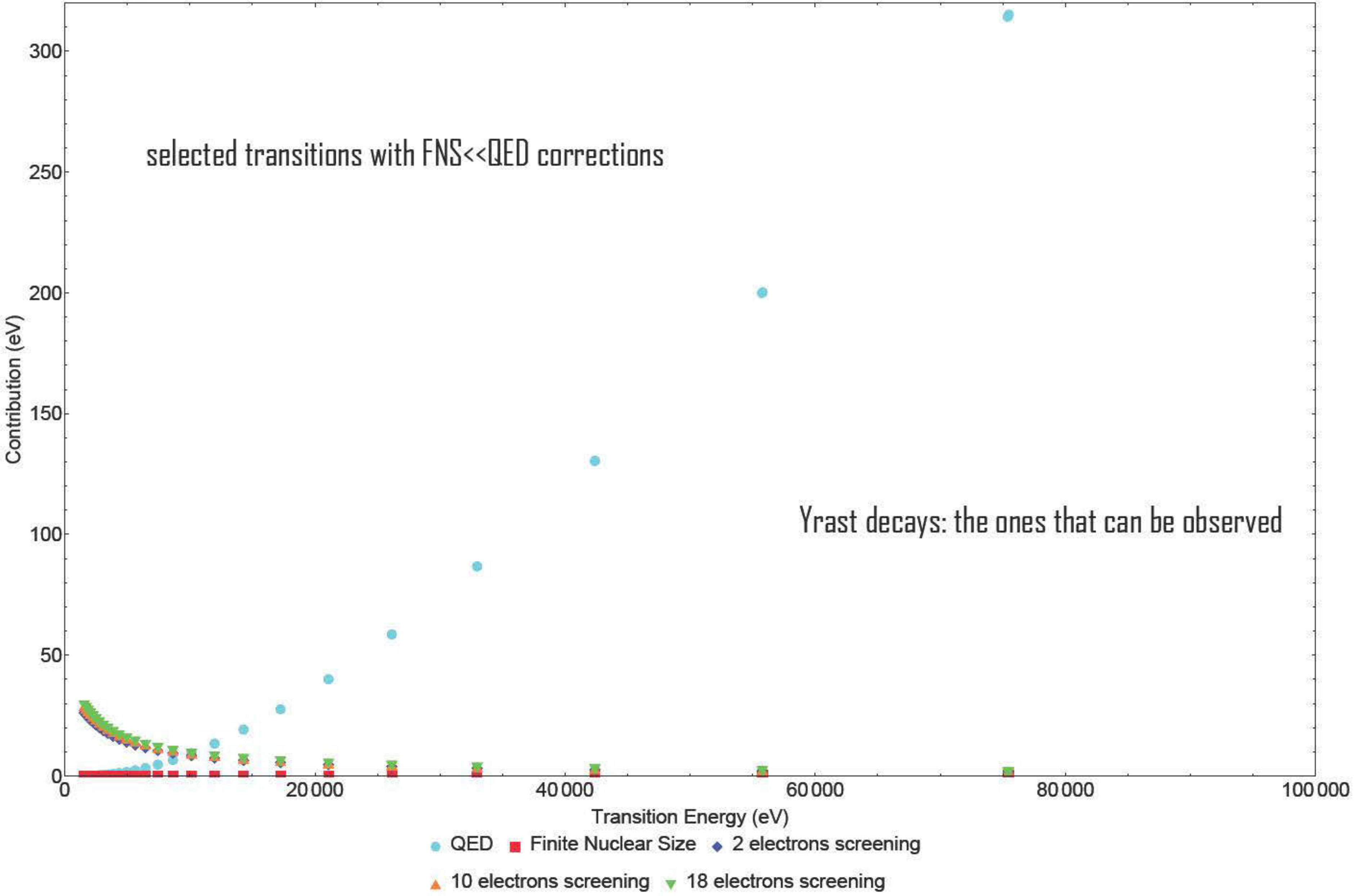
Sizes (Kr example)...

- RMS radius ^{84}Kr: 7.91x10^{-5} a.u. (4.19 fm)
- Nuclear radius (50% density): 9.05x10^{-5} a.u.
- $\bar{p}$ Kr^{36+}
  - n = 30, l=29 orbital: 1.40x10^{-2} a.u.
  - 17v orbital: 4.55x10^{-3} a.u.
  - 16u orbital: 4.04x10^{-3} a.u.
  - 1s orbital: 7.48x10^{-5} a.u.
- Kr^{35+}
  - 1s orbital: 4.07x10^{-2} a.u

antiprotonic Krypton full picture

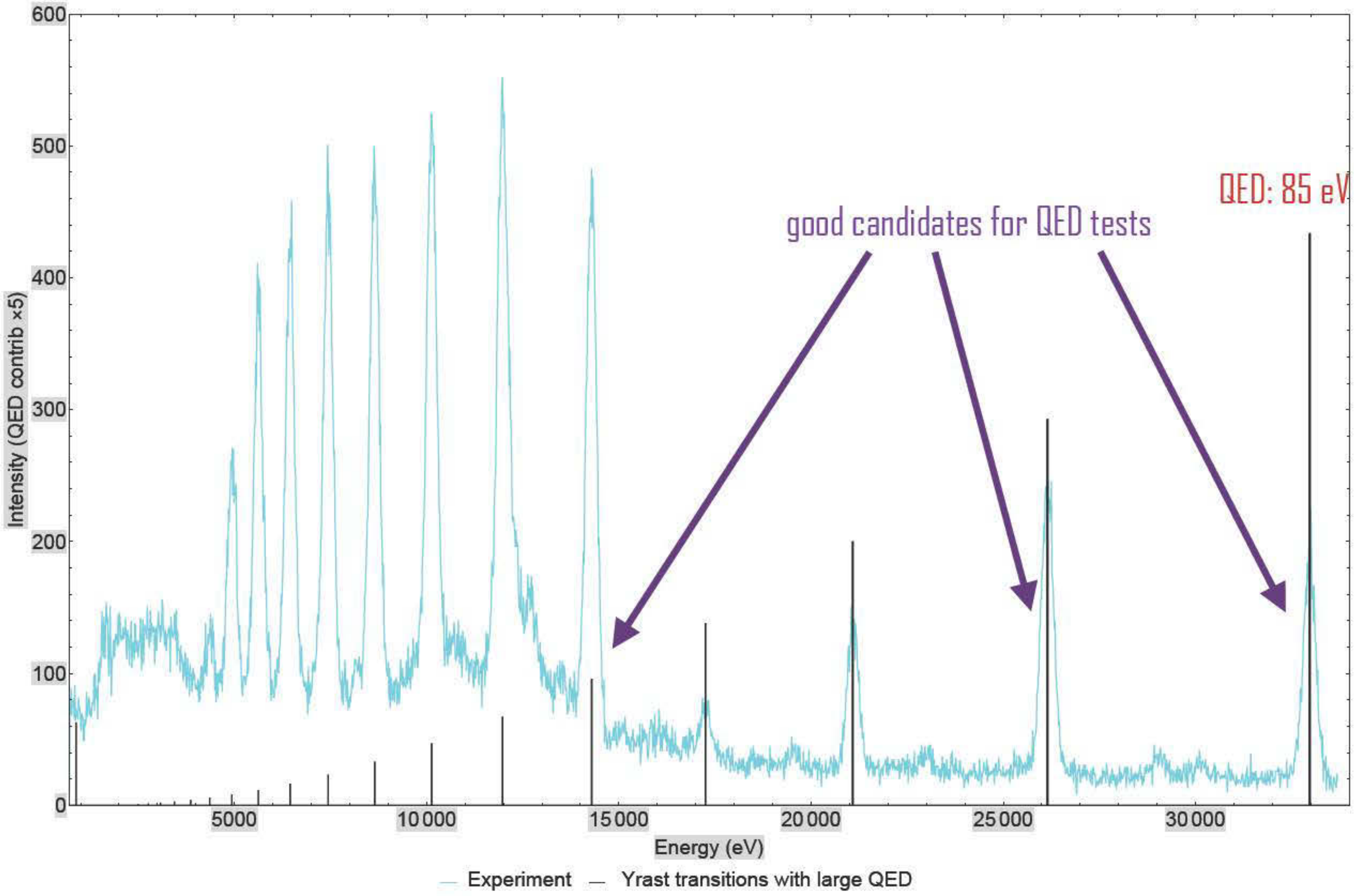


Lines with large QED and small FNS (Kr)


selected transitions with FNS<<QED corrections

Yrast decays: the ones that can be observed

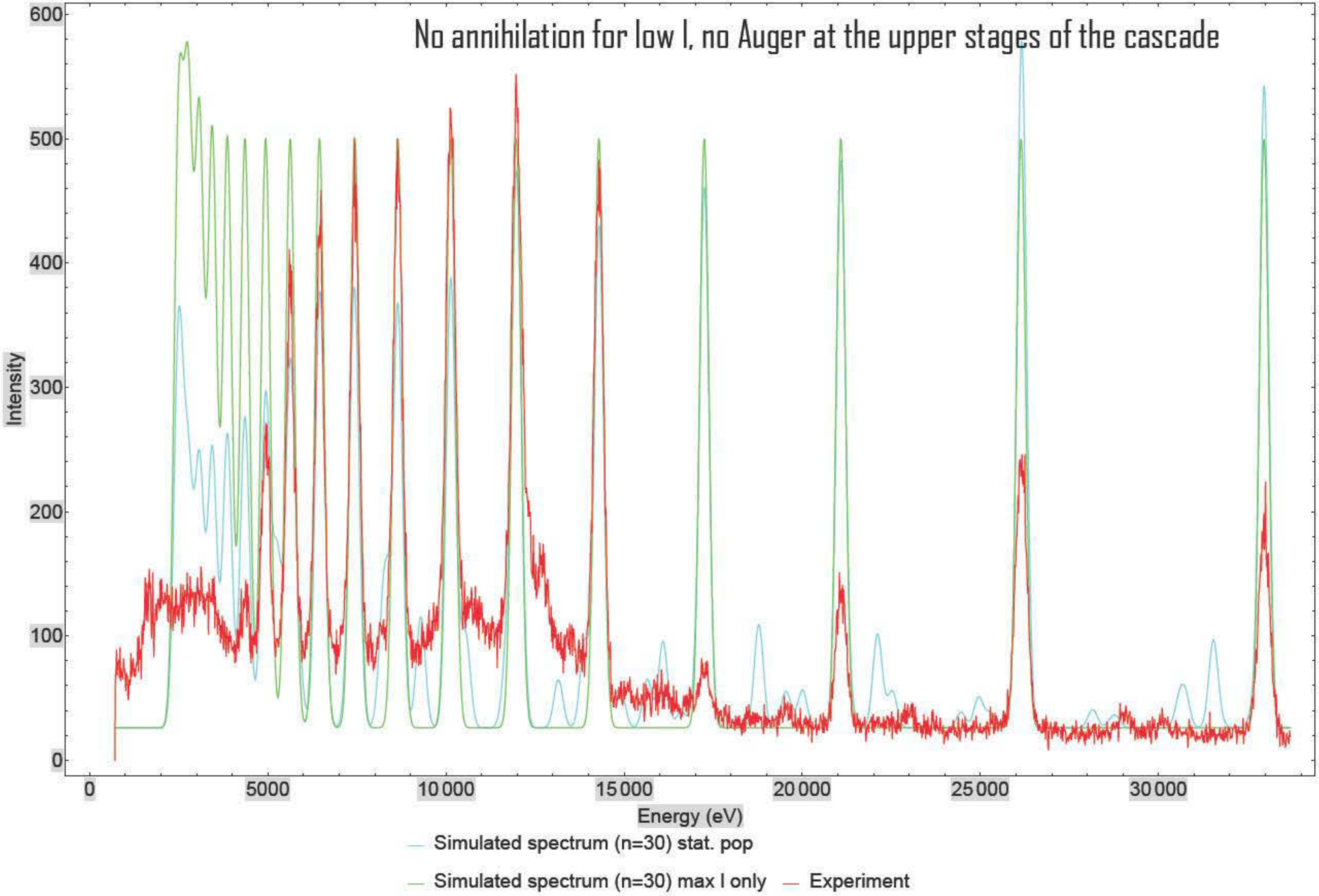
Line with large QED and no FNS (Kr)



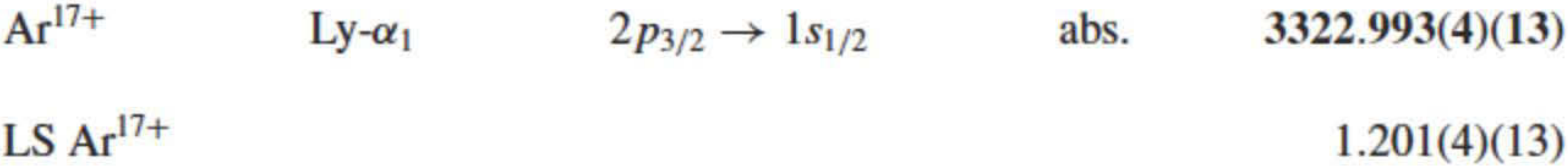
good candidates for QED tests

QED: 85 eV

Result


No annihilation for low l, no Auger at the upper stages of the cascade
Intensity
0
100
200
300
400
500
600
0
5000
10000
15000
20000
25000
30000
Energy (eV)
Simulated spectrum (n=30) stat. pop
Simulated spectrum (n=30) max l only
Experiment

H-like Ar vs antiprotonic Kr



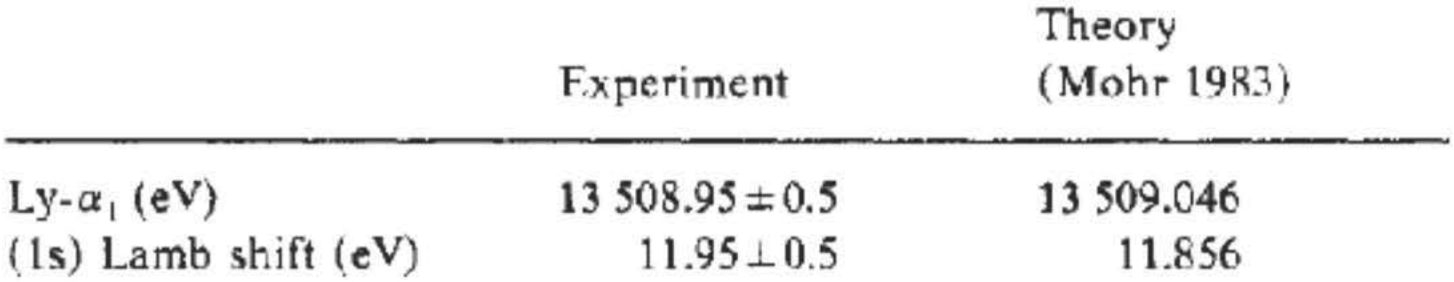
Ar^{17+}	Ly-α_1	$2p_{3/2} \to 1s_{1/2}$	abs.	**3322.993(4)(13)**
LS Ar^{17+}				1.201(4)(13)

K. Kubiček, P. H. Mokler, V. Mäckel, et al., Phys. Rev. A **90**, 032508 (2014).

Antiprotonic transition 27-26

Transition	Transition energy (eV)	QED	Nucl. Size corr.
27xx51/2→ 26zz49/2	3441.45617	-0.56596	-0.00011
27xx53/2→ 26zz51/2	3441.54138	-0.56604	-0.00010
27xx51/2→ 26uu51/2	3441.94795	-0.56616	-0.00010

H-like Kr vs antiprotonic Kr

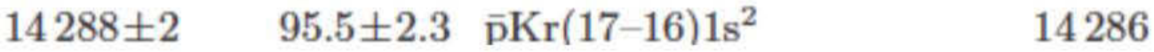


	Experiment	Theory (Mohr 1983)
Ly-α_1 (eV)	13 508.95±0.5	13 509.046
(1s) Lamb shift (eV)	11.95±0.5	11.856

M. Tavernier, J. P. Briand, P. Indelicato, et al., Journal of Physics B: Atomic, Molecular and Optical Physics **18**, L327 (1985).

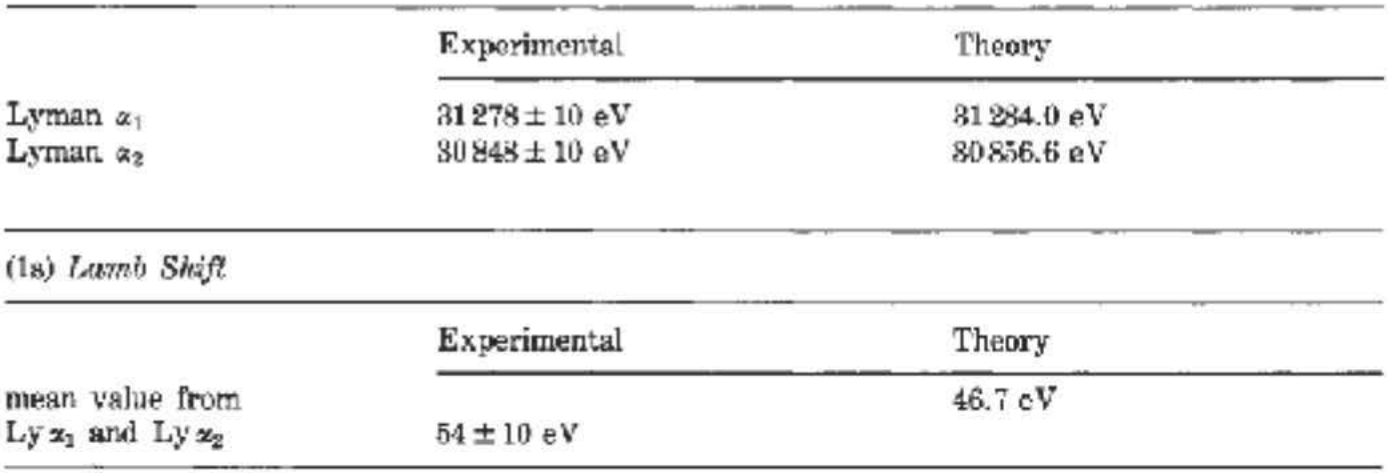
Antiprotonic transition 17v-16u

Transition	Transition energy (eV)	QED	Nucl. Size corr.
17v31/2→16u29/2	14290.6080	-19.1675	-0.0072
17v33/2→16u31/2	14292.1255	-19.1741	-0.0072
17v31/2→16u31/2	14296.3395	-19.1847	-0.0072



14 288±2	95.5±2.3	$\bar{p}$Kr(17–16)$1s^2$	14 286

H-like Xe vs antiprotonic Kr



	Experimental	Theory
Lyman α_1	31 278 ± 10 eV	31 284.0 eV
Lyman α_2	30 848 ± 10 eV	30 856.6 eV

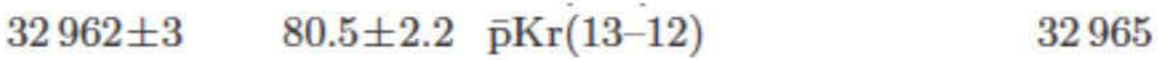
(1s) *Lamb Shift*

	Experimental	Theory
mean value from Ly α_1 and Ly α_2	54 ± 10 eV	46.7 eV

J. P. Briand, P. Indelicato, A. Simionovici, et al., Europhysics Letters **9**, 225 (1989).

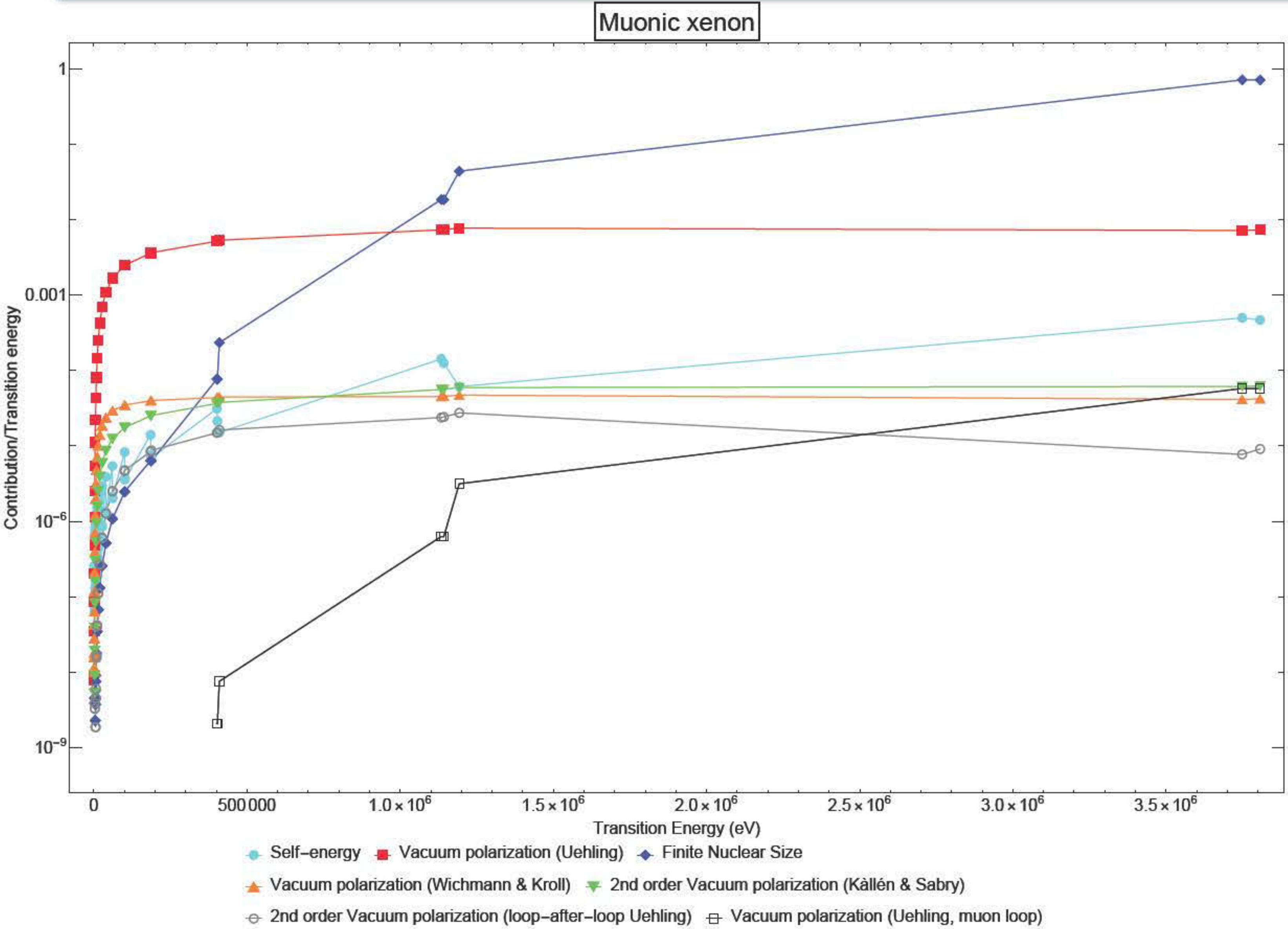
Antiprotonic transition 13q-12o

Transition	Transition energy (eV)	QED	Nucl. Size corr.
13q23/2→12o21/2	32956.86131	-86.65357	-0.06067
13q25/2→12o23/2	32965.16478	-86.71557	-0.06065
13q23/2→12o23/2	32981.63957	-86.79718	-0.06063

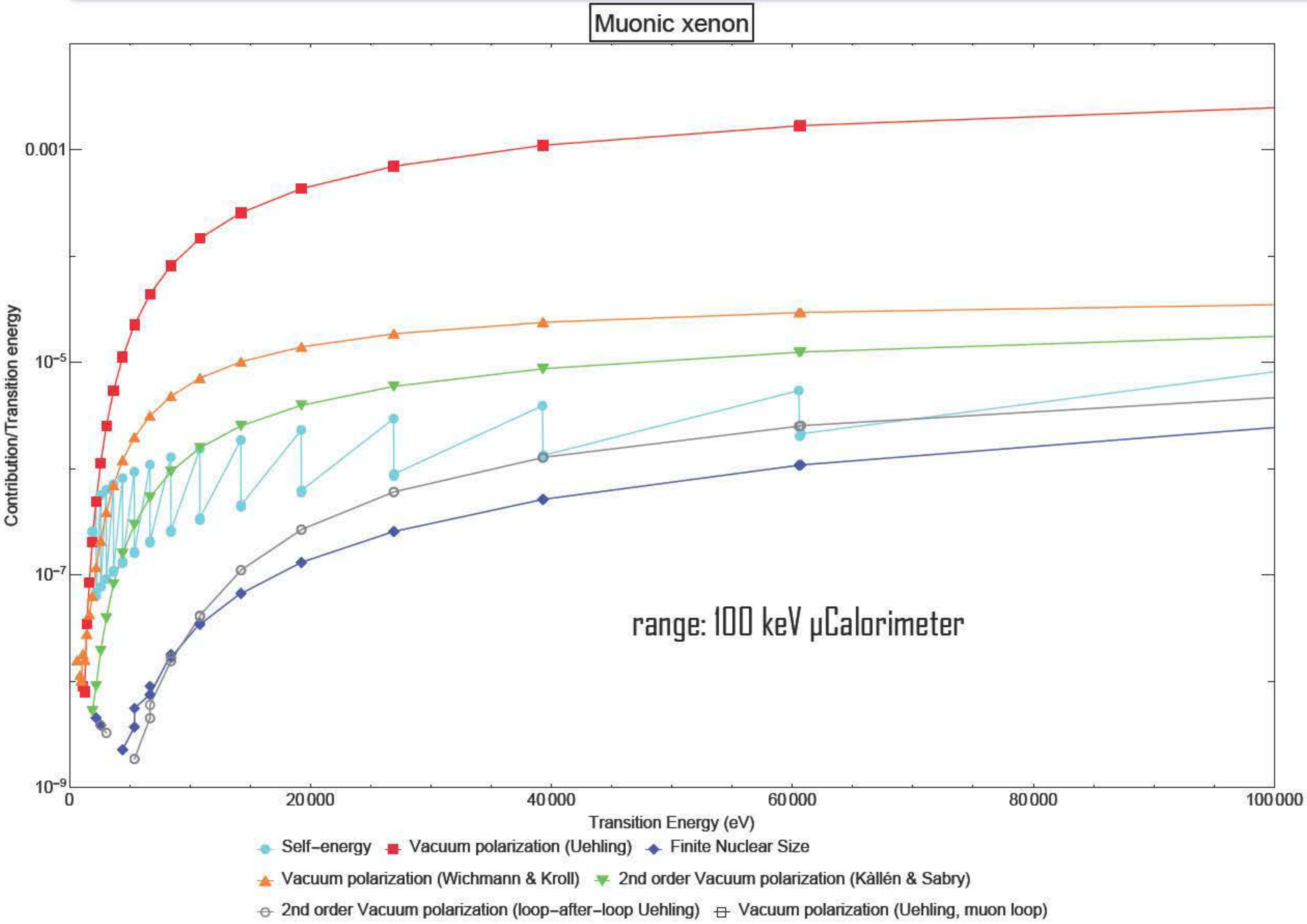


32 962±3 80.5±2.2 p̄Kr(13–12) 32 965

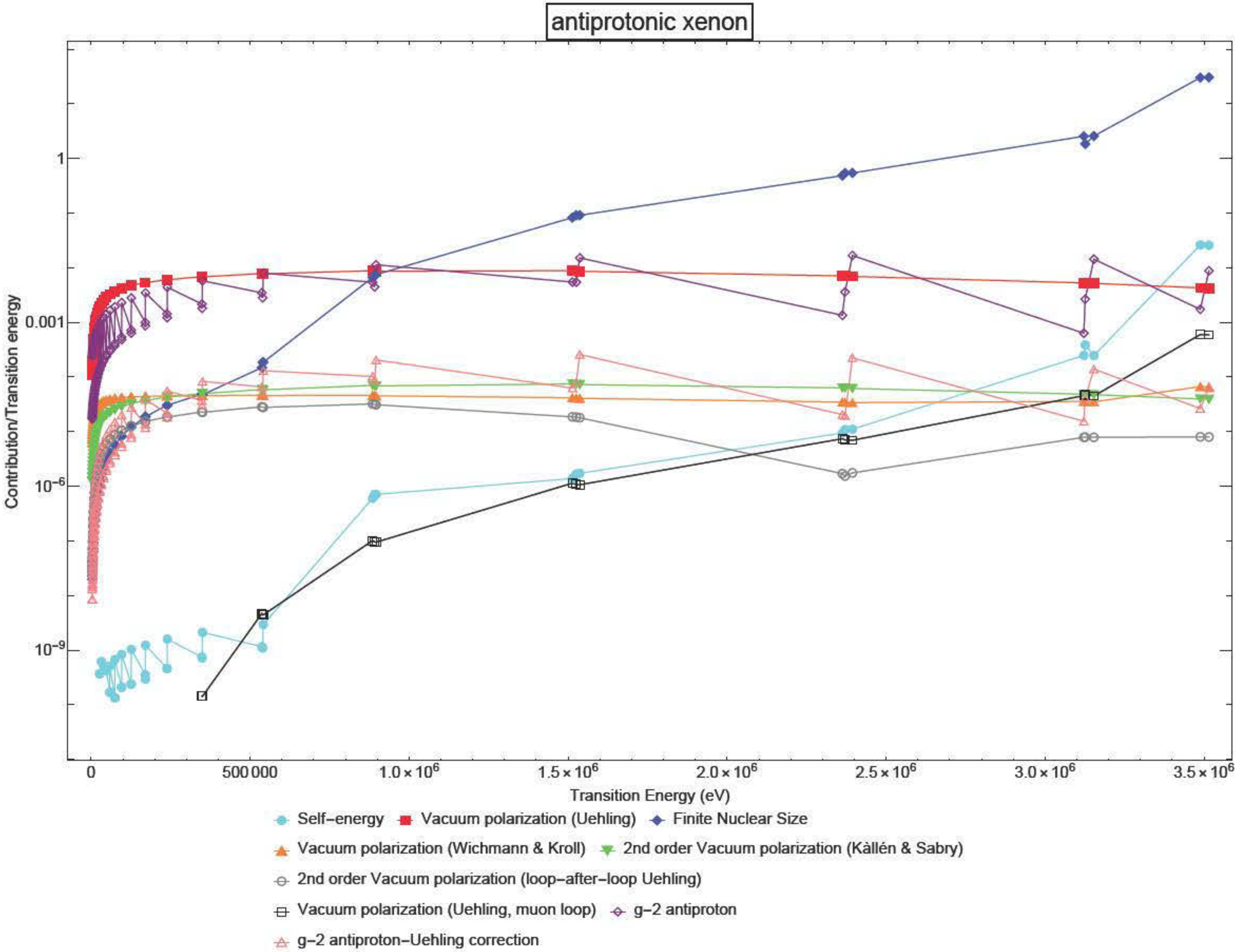
Example: muonic Xe



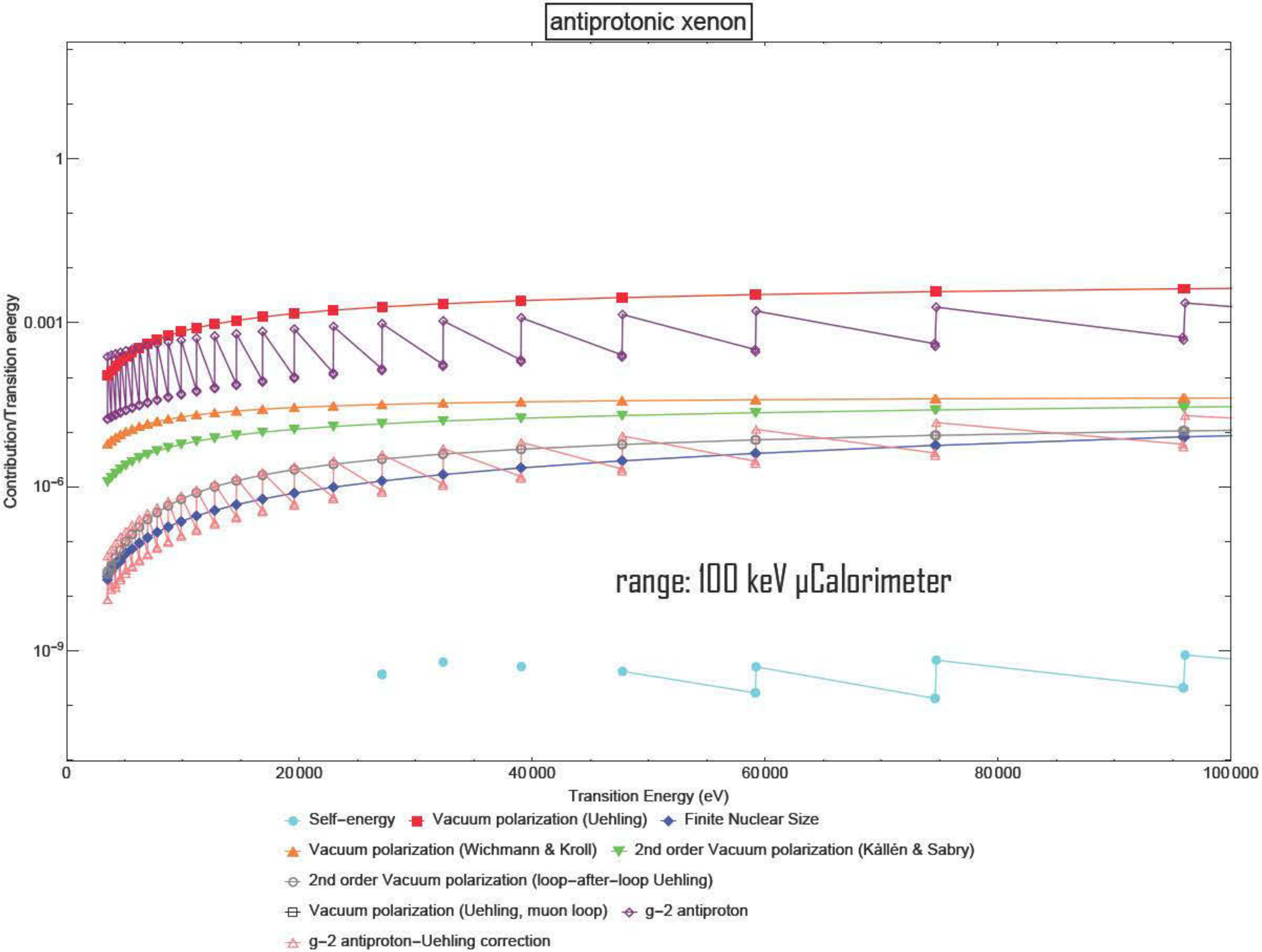
Example: muonic Xe



Example: antiprotonic Xe



Example: antiprotonic Xe



range: 100 keV µCalorimeter

First test

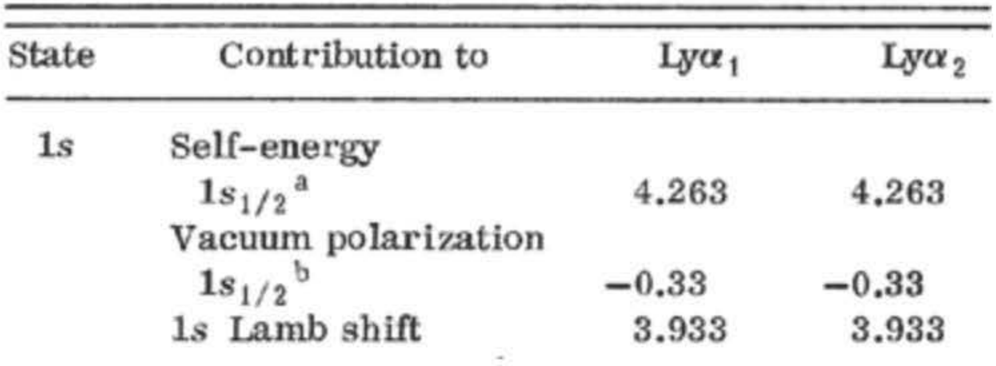
muonic Ne at J-PARC

Future with μCalorimeter

- Test experiment J-PARK April 2019: RIKEN, KEK, J-PARC, LKB, NIST (Boulder)
- 東俊行 (T. Azuma), D. A. Bennett, P. Caradonna, W.B. Doriese, J.W. Fowler, J. Gard, 橋本直 (Tadashi Hashimoto),早川亮大 (Hayakawa Ryota), G. Hilton, 一戸悠人 (Ichinohe), P. Indelicato, 磯部忠昭 (Isobe),神田聡太郎 (Sohtaro Kanda), Miho Katsugarawa, 河村成肇 (Nari Kawamura),木野康志, 三宅康博 (Y Miyake), K. Morgan,二宮和彦 (Ninokazu), 野田博文 (Hirofumi Noda), G.C. O'Neil, 岡田信二 (Shinji Okada),奥村拓馬 (O. Kumura), C. D. Reintsema, D. Schmidt,下村浩一郎 (K. Simomu), D. S. Swetz, 高橋忠幸 (Tadayuki Takahashi), Shinichiro Takeda, 竹下聡史 (S. Oshi),竜野秀行 (Hideyuki Tatsuno), 上野恭裕 (Yasuhiro Ueno), J. N. Ullom, 渡辺伸 (Watanabe), 山田真也 (S. Yamada)
- Observation of muonic Ne with NIST Boulder μCalorimeter (up to 10 keV, 4.7 eV resolution in the lab, 7 eV during beam time), 264 pixels

Comparison between H-like Fe and muonic Ne

Iron Lymanα1 line: (3.93 eV Lamb-shift for a 6973 eV line)



State	Contribution to	$Ly\alpha_1$	$Ly\alpha_2$
1s	Self-energy		
	$1s_{1/2}$[a]	4.263	4.263
	Vacuum polarization		
	$1s_{1/2}$[b]	−0.33	−0.33
	1s Lamb shift	3.933	3.933

Briand, J. P., M. Tavernier, P. Indelicato, R. Marrus and H. Gould (1983). Phys. Rev. Lett. **50**(11): 832.

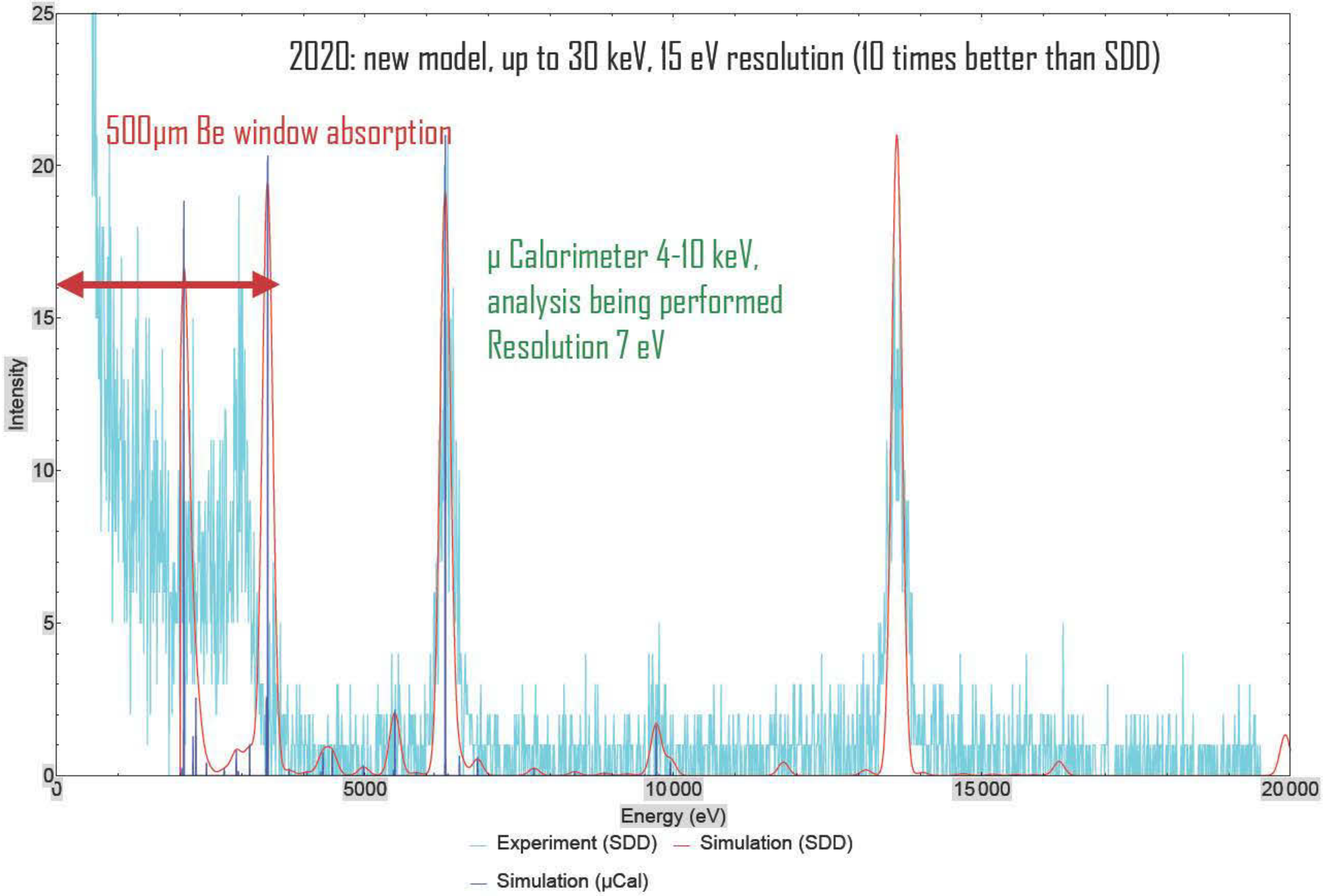
Ne $5f_{5/2} \rightarrow 4d_{3/2}$ lines we have 5.20 eV Lamb shift for 6304.34 but self-energy is only 0.003 eV while Vac. Pol. is 5.16 eV

We have a higher QED contribution for a lower transition energy

Reverse usual idea: look for lines with large QED and small FNS

Experiment at J-PARC

Exemple of SDD spectrum of µNe



2020: new model, up to 30 keV, 15 eV resolution (10 times better than SDD)

500µm Be window absorption

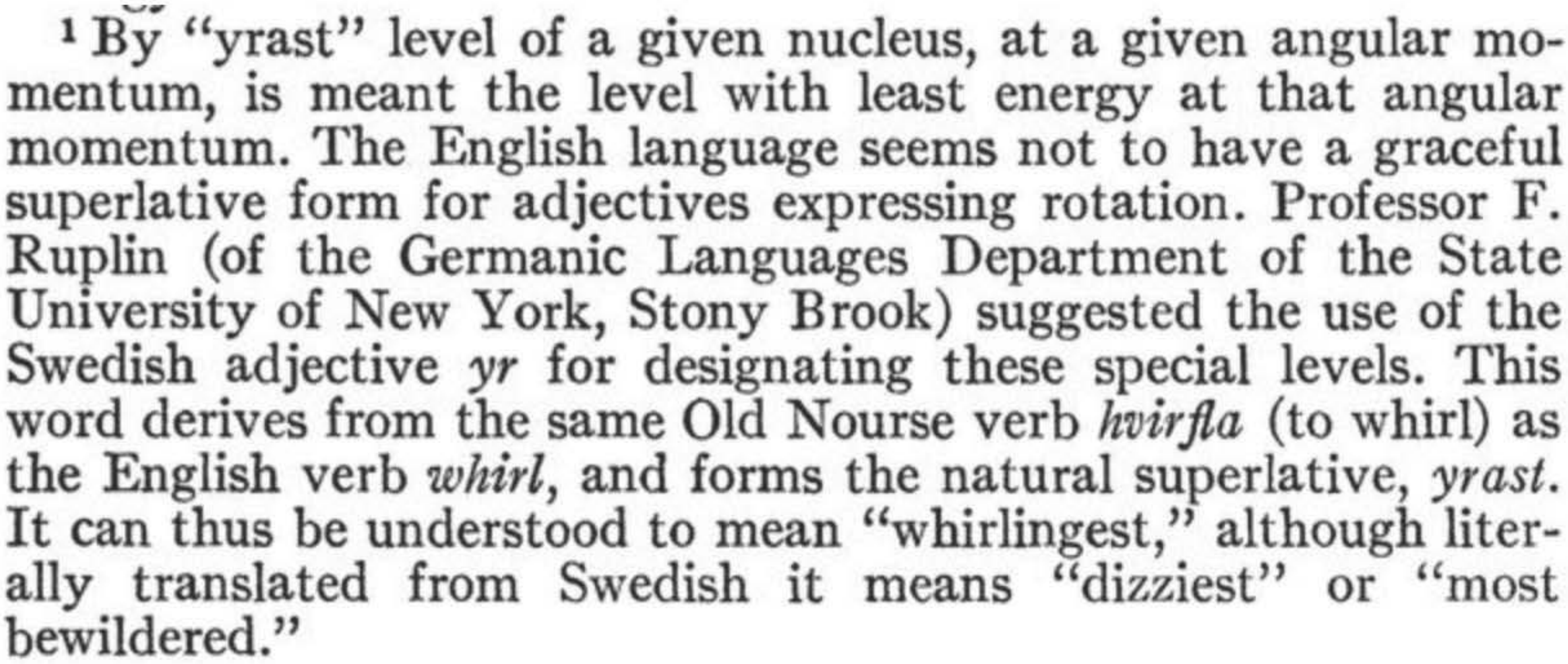
µ Calorimeter 4-10 keV,
analysis being performed
Resolution 7 eV

Starting n = 15, statistical distribution on the initial state

Conclusion

- The « proton size puzzle » is still alive
- There are apparently no problem with QED in normal ions
- Nuclear size effects for lower levels strongly dominates the transition energy values
- One can find, in both muonic and $\bar{p}$ atoms, transitions with lamb-shift contributions as large or larger than in electronic highly-charged ions, that can be measured precisely using modern techniques like μ-Calorimeters
- QED corrections are dominated by vacuum polarization while they are dominated by self-energy in normal atoms
- More work:
  - 1st-order self-energy with realistic potentials
  - 2nd order QED diagrams with mixed SE-VP loops
  - add Auger to transitions/level width code (!?)

Thank you for your attention 😀



[1] By “yrast” level of a given nucleus, at a given angular momentum, is meant the level with least energy at that angular momentum. The English language seems not to have a graceful superlative form for adjectives expressing rotation. Professor F. Ruplin (of the Germanic Languages Department of the State University of New York, Stony Brook) suggested the use of the Swedish adjective *yr* for designating these special levels. This word derives from the same Old Nourse verb *hvirfla* (to whirl) as the English verb *whirl*, and forms the natural superlative, *yrast*. It can thus be understood to mean “whirlingest,” although literally translated from Swedish it means “dizziest” or “most bewildered.”

J. Robb Grover, Phys. Rev. **157**, 832 (1967)