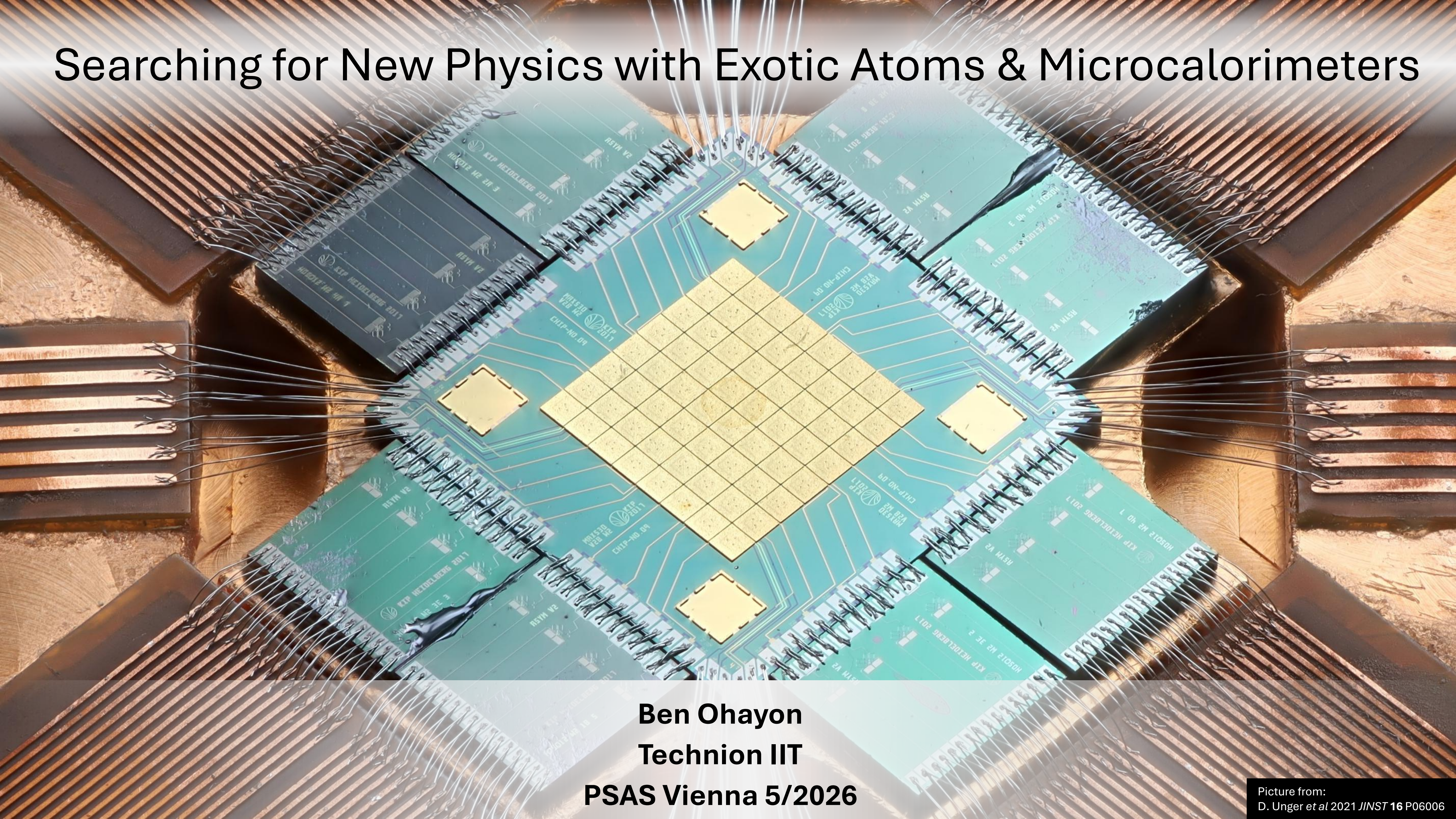
Searching for New Physics with Exotic Atoms & Microcalorimeters



Ben Ohayon

Technion IIT

PSAS Vienna 5/2026

Picture from:
D. Unger *et al* 2021 *JINST* **16** P06006

Today

- Intro: Compact Exotic Atoms
- New physics searches with antiProtonic atoms
- New physics searches with Contact-free muonic atoms
- If there is time: a new relevant initiative ...

Today

- **Intro: Compact Exotic Atoms**

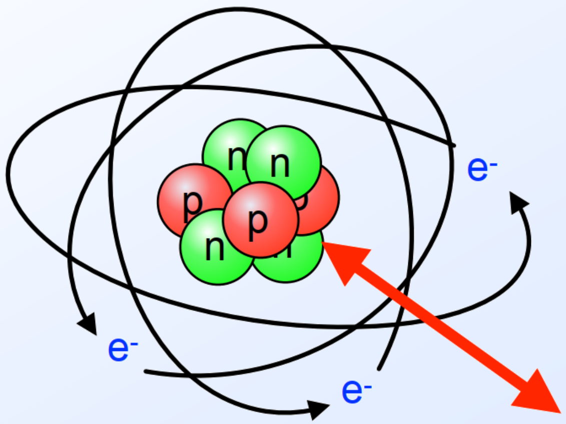
- New physics searches with antiProtonic atoms

- New physics searches with <u>Con</u>tact-<u>fr</u>ee mu<u>on</u>ic a<u>t</u>oms

- If there is time: a new relevant initiative ...

Exotic Atoms:

Replace nucleus with positive particle:



e^+, μ^+

Positronium
Muonium
Pionium
...

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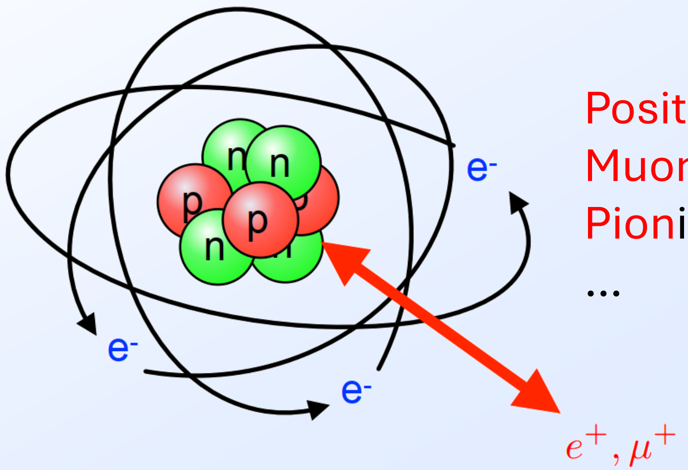
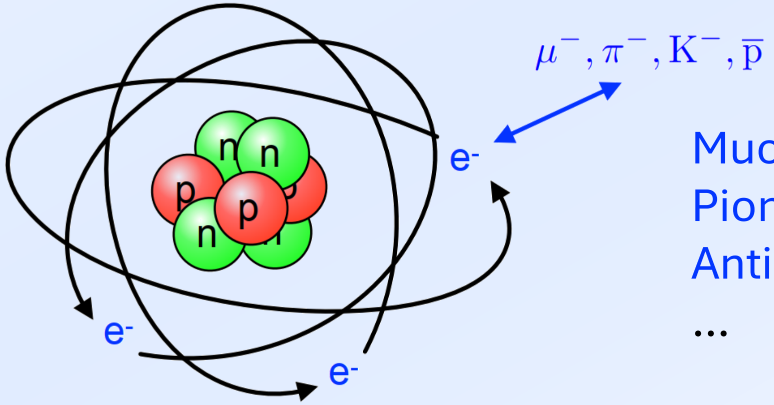


Positronium
Muonium
Pionium
...

Replace electron(s) with negative particle:



Muonic hydrogen
Pionic Helium
Antiprotonic Helium
...

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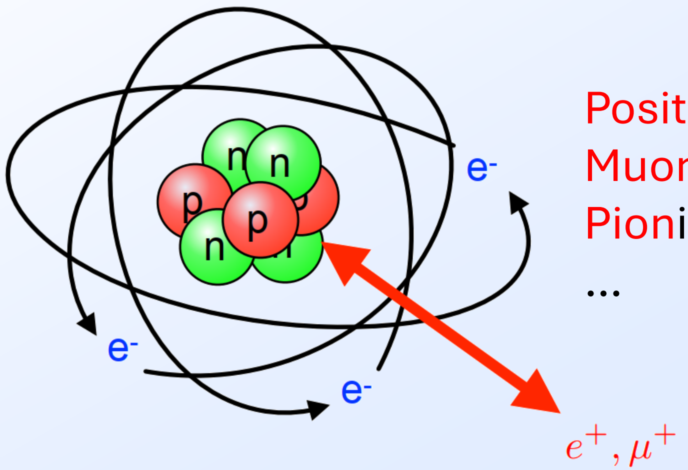

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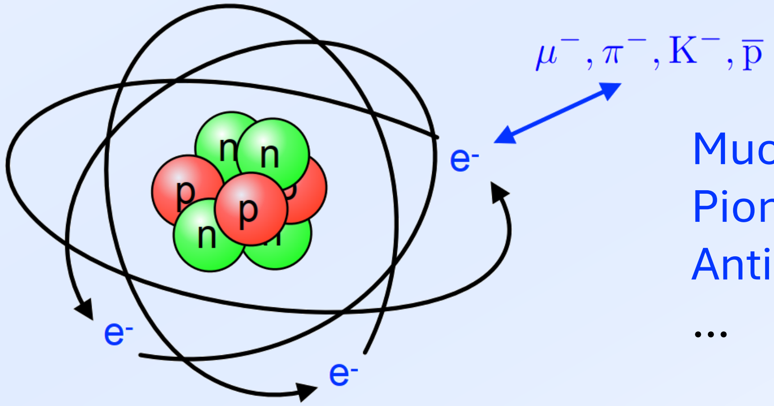

Muonic hydrogen
Pionic Helium
Antiprotonic Helium
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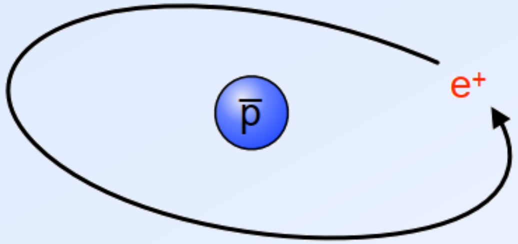
Or replace **both**:



Anti-Hydrogen

Exotic Atoms:

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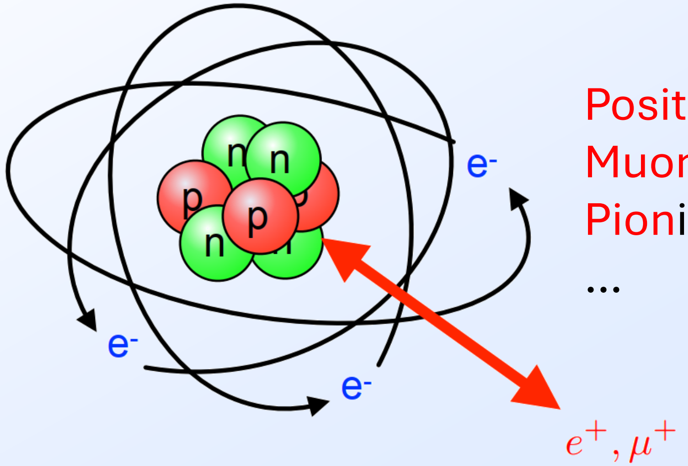

Positronium
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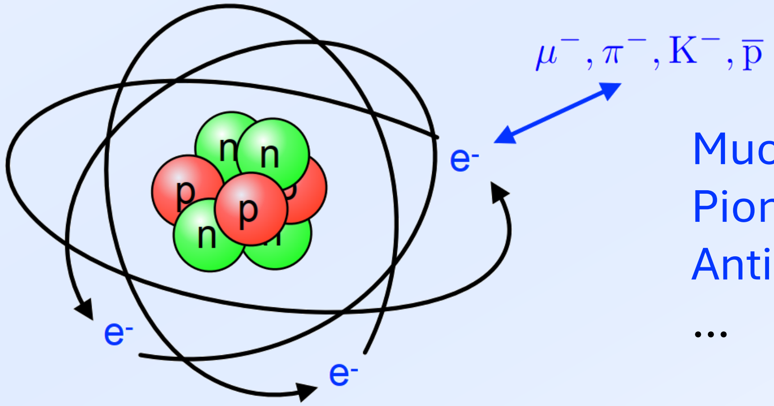

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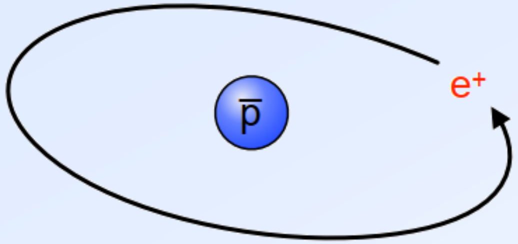
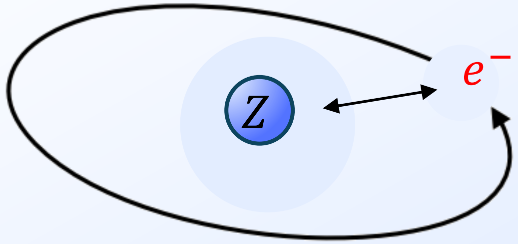
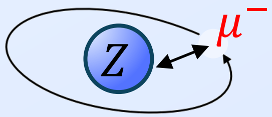


Anti-Hydrogen

"Compact systems"

Muonic vs. electronic atoms:





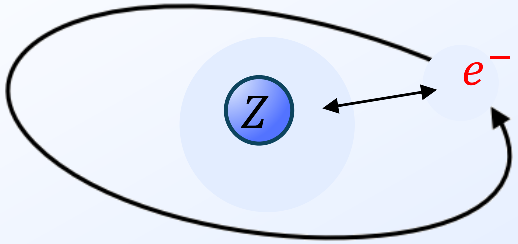
Characteristic **length**

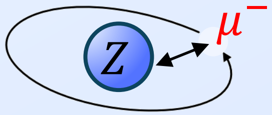
(Bohr radius: $a_0 = \frac{\hbar}{m_e c \alpha} \sim 0.5\text{Å}$):

$$a_n \approx \frac{n^2 a_0}{Z} \xrightarrow{/200} \frac{n^2 a_0}{Z} \frac{m_e}{m_\mu}$$

Shorter distances

Muonic vs. electronic atoms:





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(Rydberg: $R_\infty = \frac{\hbar c\alpha}{2a_0} \sim 13.6\ eV$):

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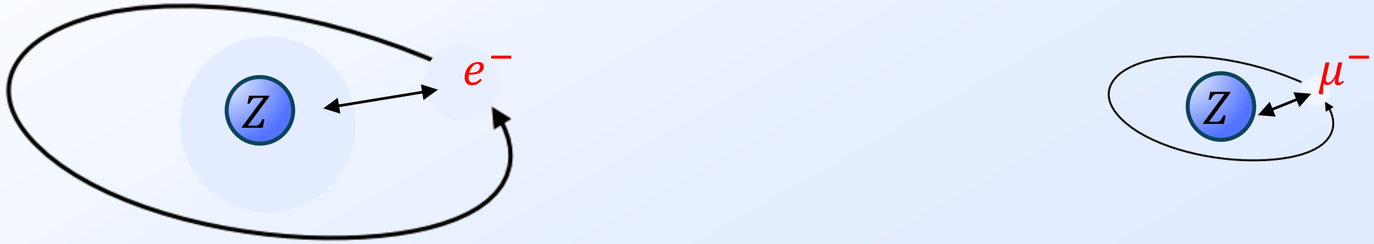
$MW \rightarrow Laser$

$Laser \rightarrow x - ray$

Higher energies

Muonic vs. electronic atoms:



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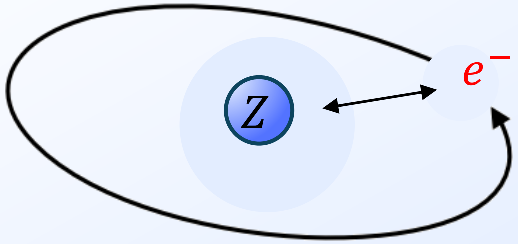
Higher energies

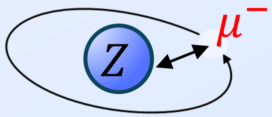
Characteristic Field
($\frac{2R_\infty}{ea_0} \sim 54\frac{V}{\text{Å}} \sim 10^{12} V/m$):

$$F_n = \frac{E_n}{ea_n} \approx -\frac{2R_\infty Z^3}{ea_0 n^3} \xrightarrow{\times (200)^2} F_n \approx -\frac{2R_\infty Z^3}{ea_0 n^3}\left(\frac{m_\mu}{m_e}\right)^2$$

Extreme fields

Muonic vs. electronic atoms:





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Extreme fields

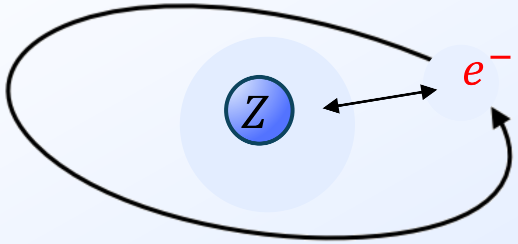
Nuclear Size effect:

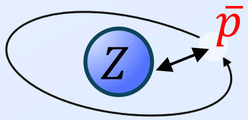
$$\Delta E_{FNS} \sim \frac{4}{3}\frac{R_\infty Z^4}{n^3}\left(\frac{r_c}{a_0}\right)^2 \delta_{l0} \xrightarrow{\times (200)^3} \frac{4}{3}\frac{R_\infty Z^4}{n^3}\left(\frac{r_c}{a_0}\right)^2 \left(\frac{m_\mu}{m_e}\right)^3 \delta_{l0}$$

Strong overlap

In a nonrelativistic approximation, nuclear effects predominantly produce “contact terms” that affect the “s” states

AntiProtonic vs. electronic atoms:





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- Contact free muonic atoms
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Searching for new physics with Exotic atoms

Theory

Experiment

Searching for new physics with Exotic atoms

Theory

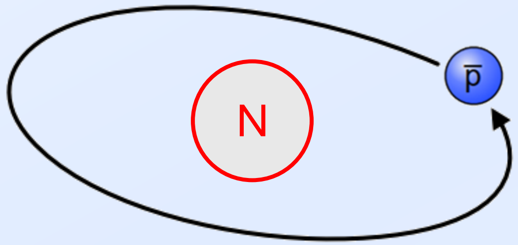
Experiment

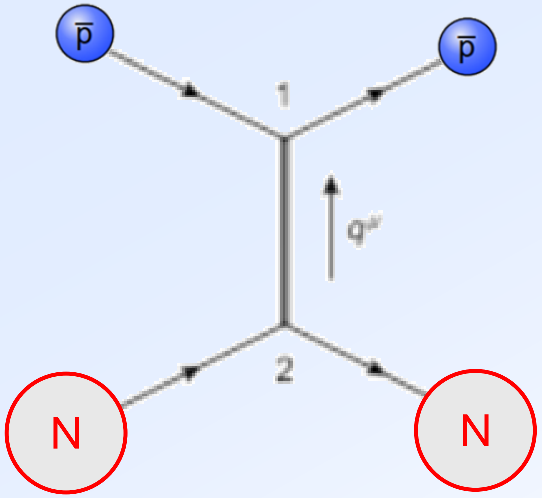
New Physics?

Why compact atoms?

The potential:

$$V_X(\boldsymbol{r}) = (-1)^s \frac{g_N^X g_H^X}{4\pi} \frac{e^{-m_X r}}{r}$$





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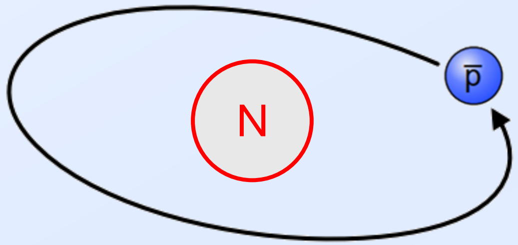

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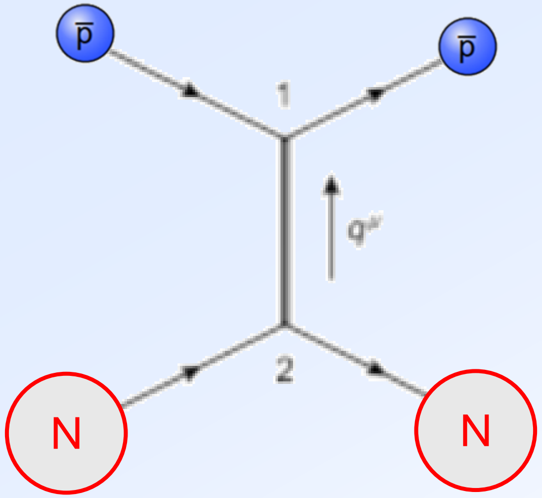

Changes the energies of circular states ($n = l + 1$):

$$E_n^X = (-1)^s \frac{g_H^X g_N^X}{4\pi} \frac{1}{r_n} \frac{1}{\left(1 + \frac{m_X r_n}{2n}\right)^{2n}}$$

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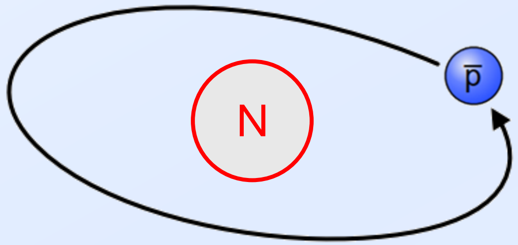

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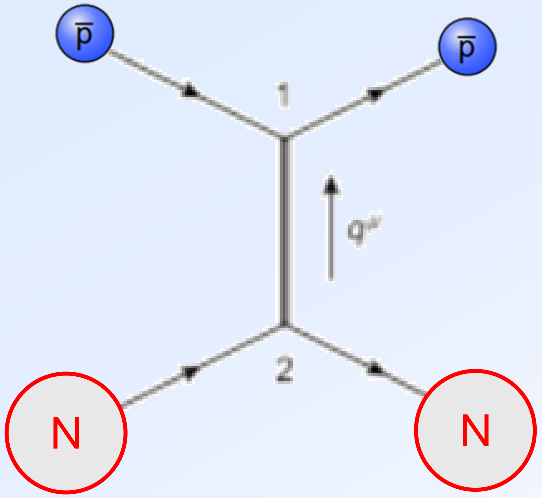

Beyond the **decoupling radius**, the sensitivity drops:

$$r_n \equiv n^2/(Z\alpha\mu)$$

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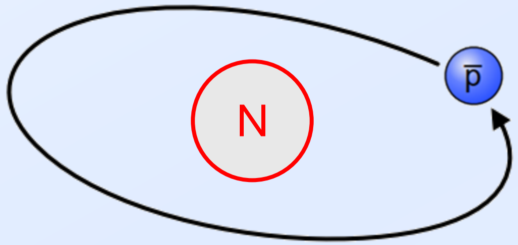

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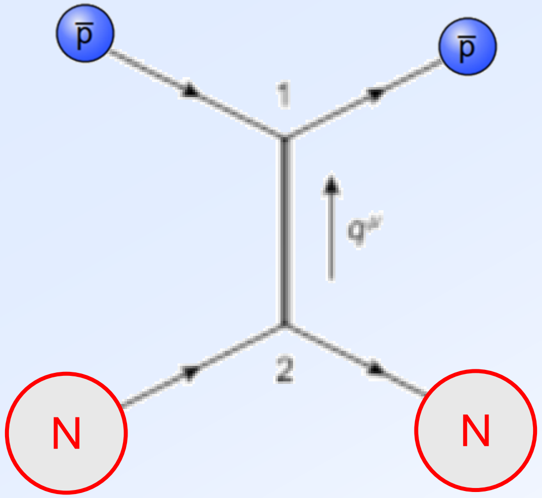


Beyond the **decoupling radius**, the sensitivity drops:

$$r_n \equiv n^2/(Z\alpha\mu)$$

The higher the mass, the more sensitive we are !

For $\mathrm{m_e}, 1/r_n \approx \mathrm{keV}$

For $\mathrm{m_p}, 1/r_n \approx \mathrm{MeV}$

Compact atoms give:

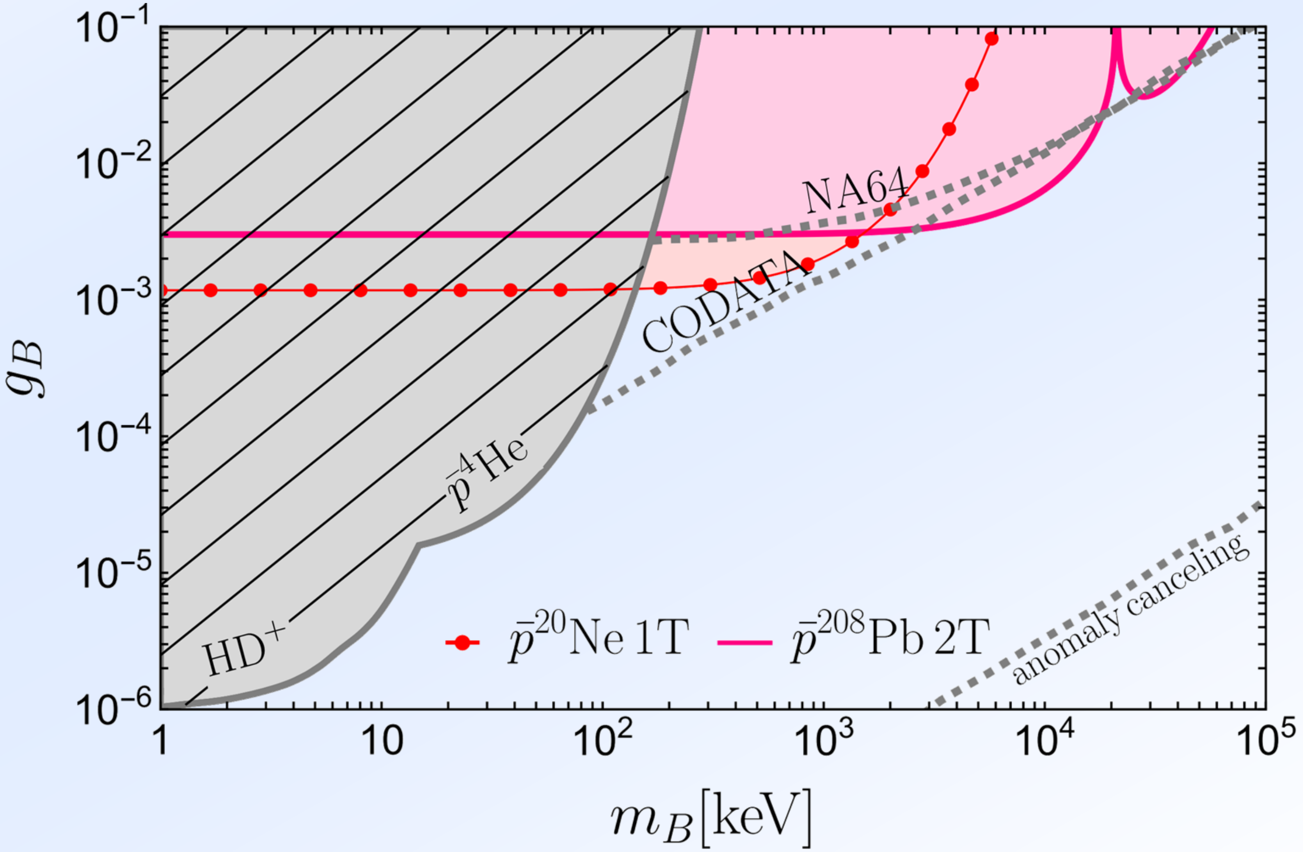
Access to short distances

Sensitivity to specific couplings

Existing bounds from hadronic atoms

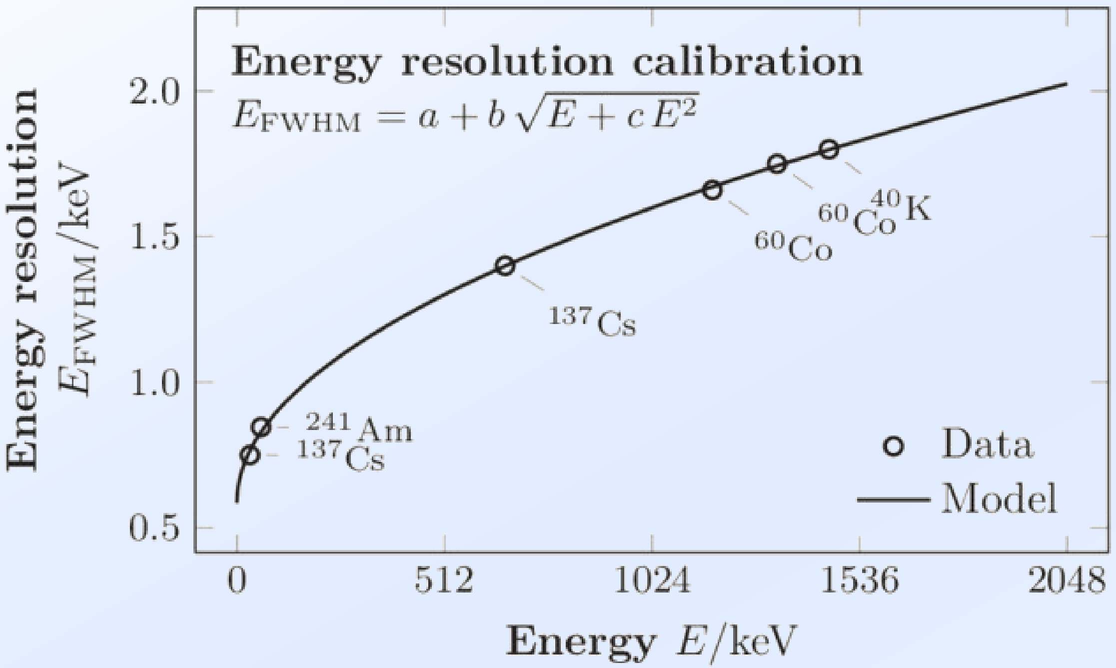
PRL **135**, 131803

Bound-state	(n_i, l_i)	(n_f, l_f)	$E^{\mathrm{SM,LO}}_{n,n-1}$ [keV]	$\Delta_{n,n-1}/E^{\mathrm{SM,LO}}_{n,n-1}$ [ppm]	$1/r_{n_f}$ [MeV]	$E^{\mathrm{NPol}}_{n,n-1}/E^{\mathrm{SM,LO}}_{n,n-1}$ [ppm]
$\pi^-\ {}^{14}\mathrm{N}$	(5,4)	(4,3)	4.05	3.9 ± 1.7 [47]	0.44	0.005
$\bar{p}\ {}^4\mathrm{He}$	(32,31)	(31,30)	5.11×10^{-3}	$(2.2 \pm 2.3) \times 10^{-3}$ [73]	0.011	10^{-8}
$\bar{p}\ {}^{20}\mathrm{Ne}$	(13,12)	(12,11)	2.44	14 ± 23 [39]	0.45	0.005
$\bar{p}$ Pb	(12,11)	(11,10)	221	109 ± 77 [65, 66]	4.6	20
$\bar{p}$ Pb	(11,10)	(10,9)	290	114 ± 72 [65, 66]	5.5	40

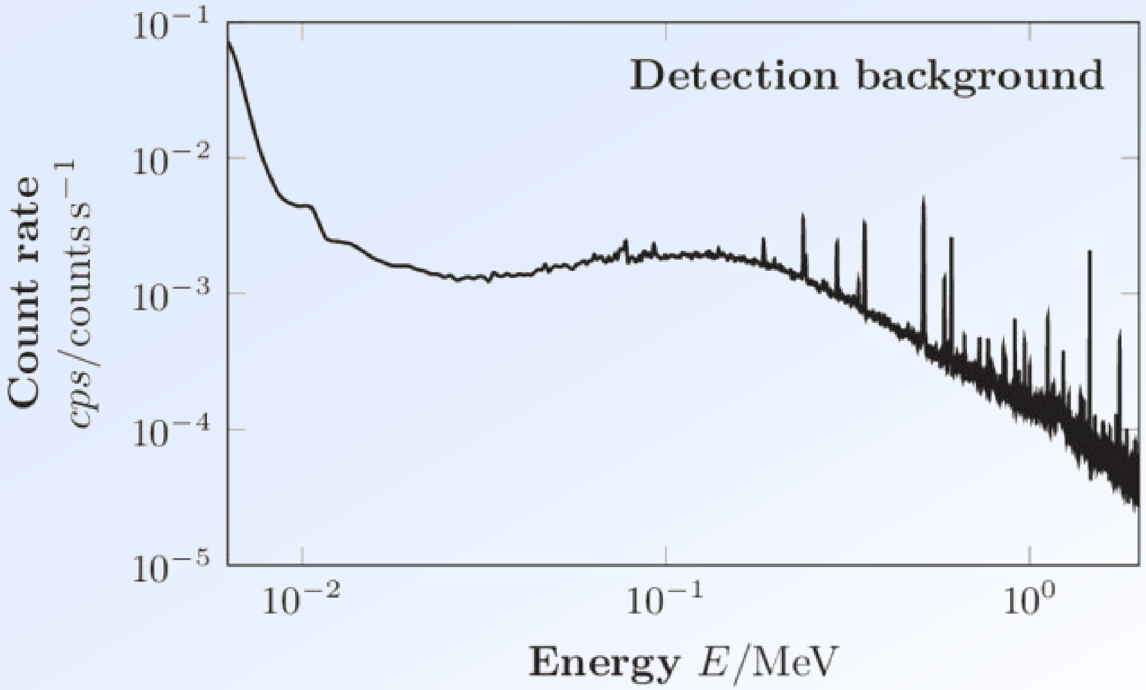


At the low energies, mostly relevant to new physics searches

We were limited by existing detection technologies



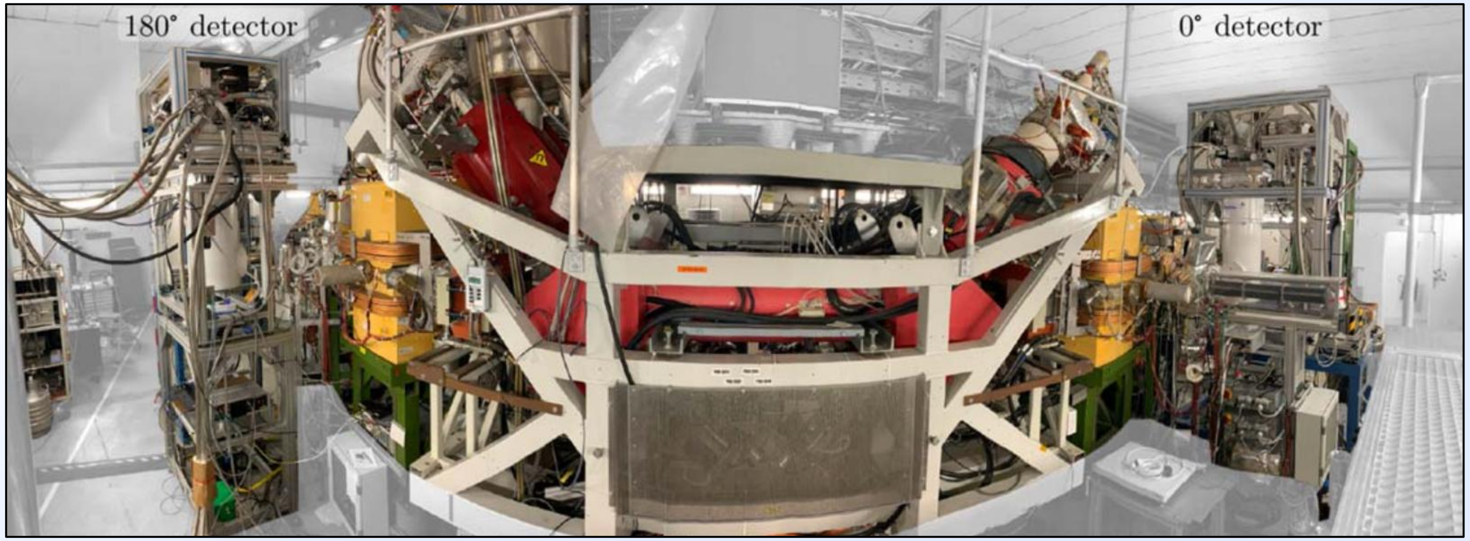
Resolving power deteriorates



Background increases

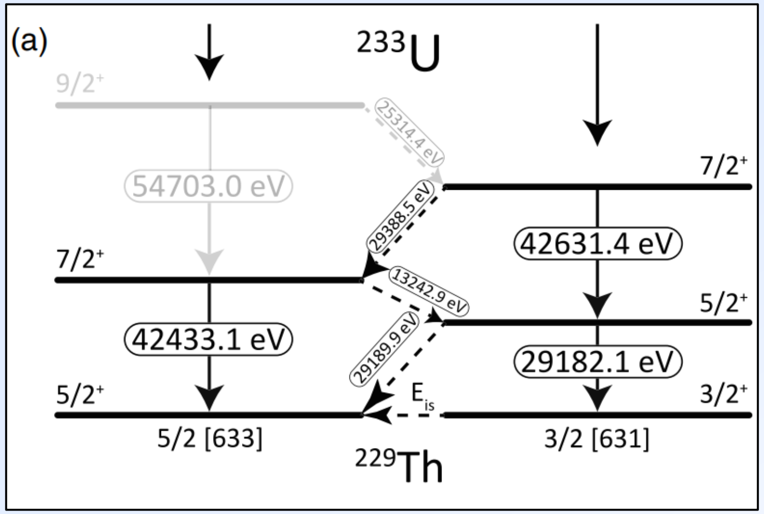
Enter Microcalorimeters

X-ray spectroscopy of highly charged ions @ storage rings



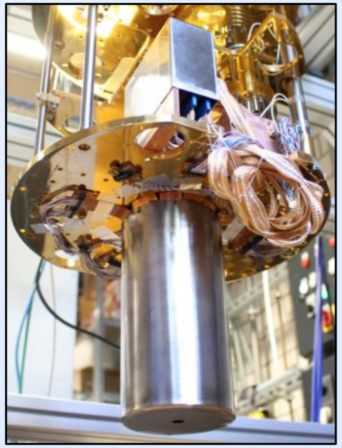
Ph. Pfäfflein, *et. al.,* Phys. Scr. 97 (2022). M.O. Herdrichet. *al.,* Atoms 11, 13 (2023), …

^{229m}Th optical excitation energy 8.1(2) eV:



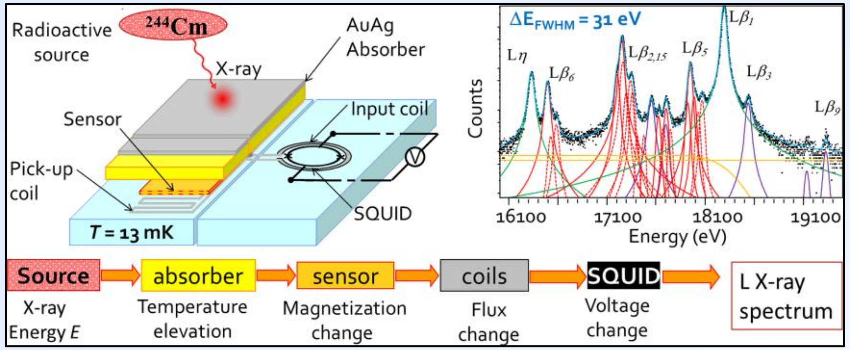
Th Sikorsky, *et. al.,* PRL 125, 142503 (2020)

Search for Axion-like particles:



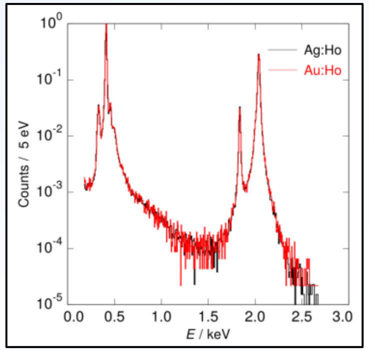
D. Unger, L. Gastaldo, A. Fleischmann, *et. al.,* JINST 16 (2021)

Determination X-ray absolute emission intensities:



R Mariam, *et. al.,* Spectrochimica Acta B 187 (2022)

Electron capture in ^{163}Ho:

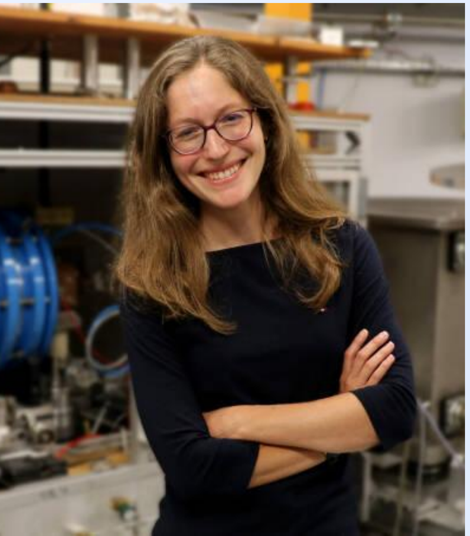


L. Gastaldo, A. Fleischmann, *et. al.,*
Journal of Low Temperature Physics 209 (2022)

antiProtonic Atom X-ray spectroscopy

Michael Roosa's Talk on Wednesday !

- Testing high-field QED with antiprotonic atoms
- Target circular transitions in noble gasses
- Employ microcalorimeter detectors



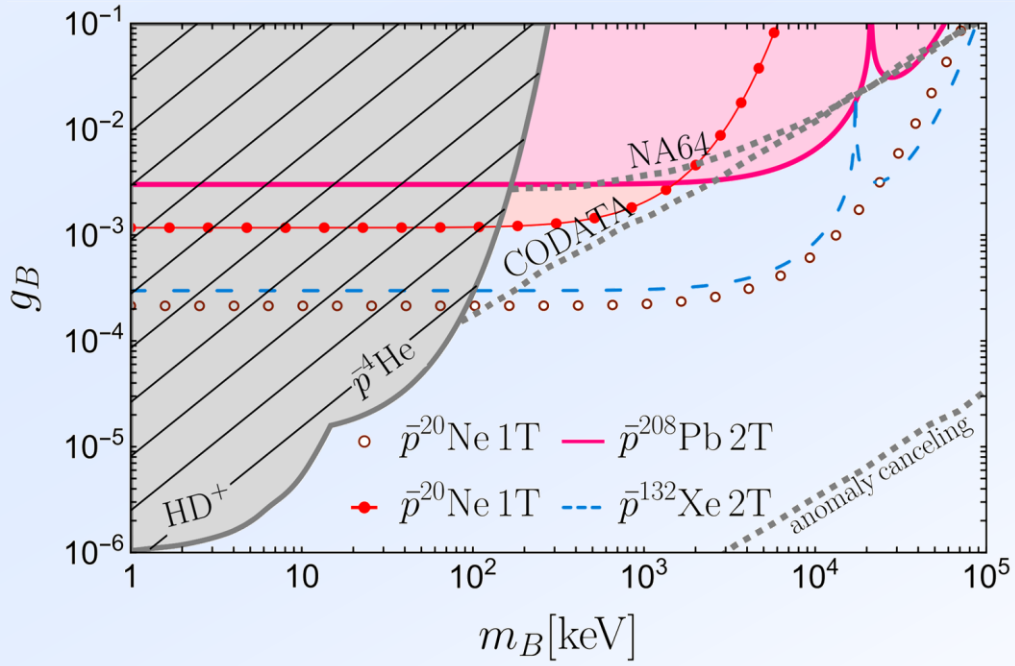
Spokesperson: Nancy Paul
npaul@lkb.upmc.fr

Prospects p̄AX (at ppm accuracy) PRL **135**, 131803

Bound state	(n_i, l_i)	(n_f, l_f)	$E^{\mathrm{SM,LO}}_{n,n-1}$ [keV]	$/r_{n_f}$ [MeV]	$E^{\mathrm{NPol}}_{n,n-1}/E^{\mathrm{SM,LO}}_{n,n-1}$ [ppm]
$\bar{p}^{20}$Ne	(6,5)	(5,4)	29.0	2.6	1
$\bar{p}^{132}$Xe	(11,10)	(10,9)	125	3.7	8
$\bar{p}^{132}$Xe	(10,9)	(9,8)	170	4.5	20

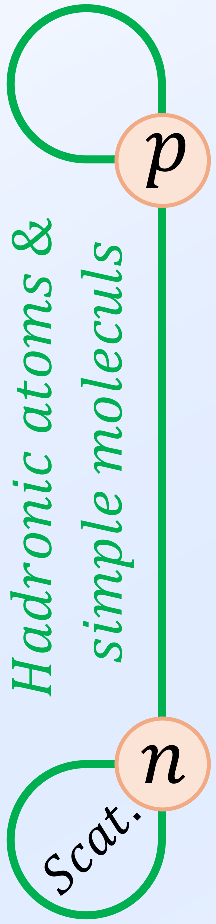
<u>**Energies in the 20-200 keV range**</u>

Sensitive to new bosons with MeV masses !



PAX experiment could search for new physics well-beyond the state of the art !

Panorama of heavy boson searches:



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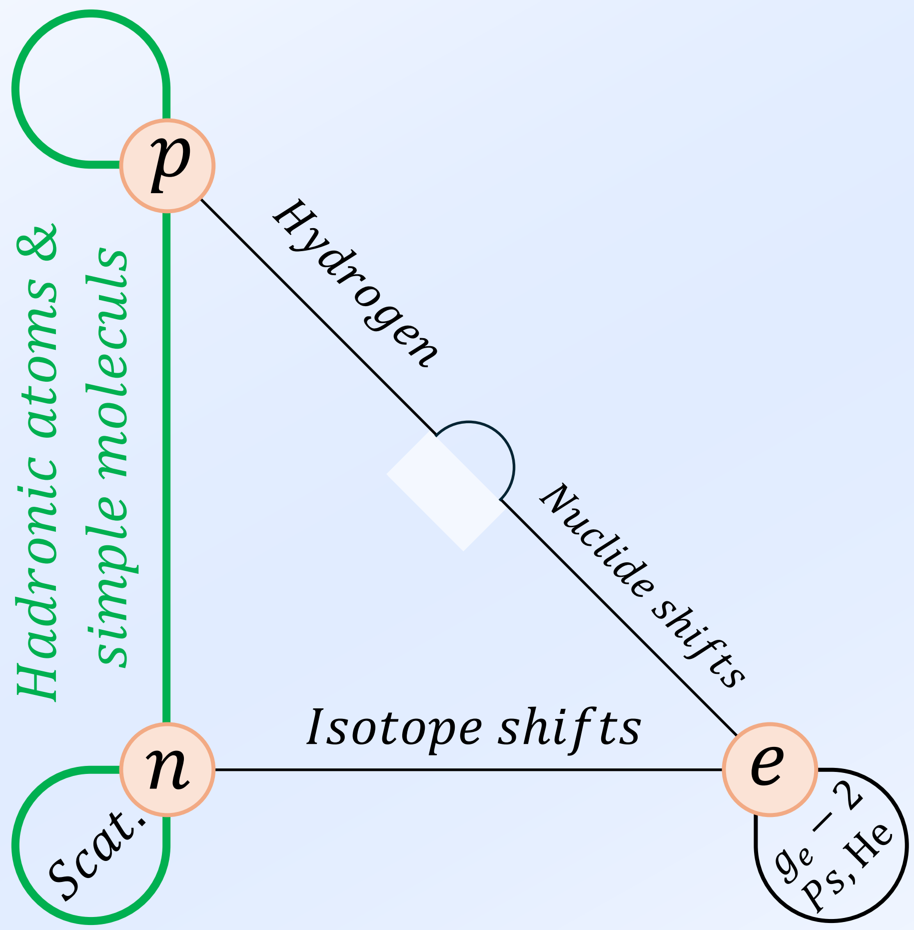

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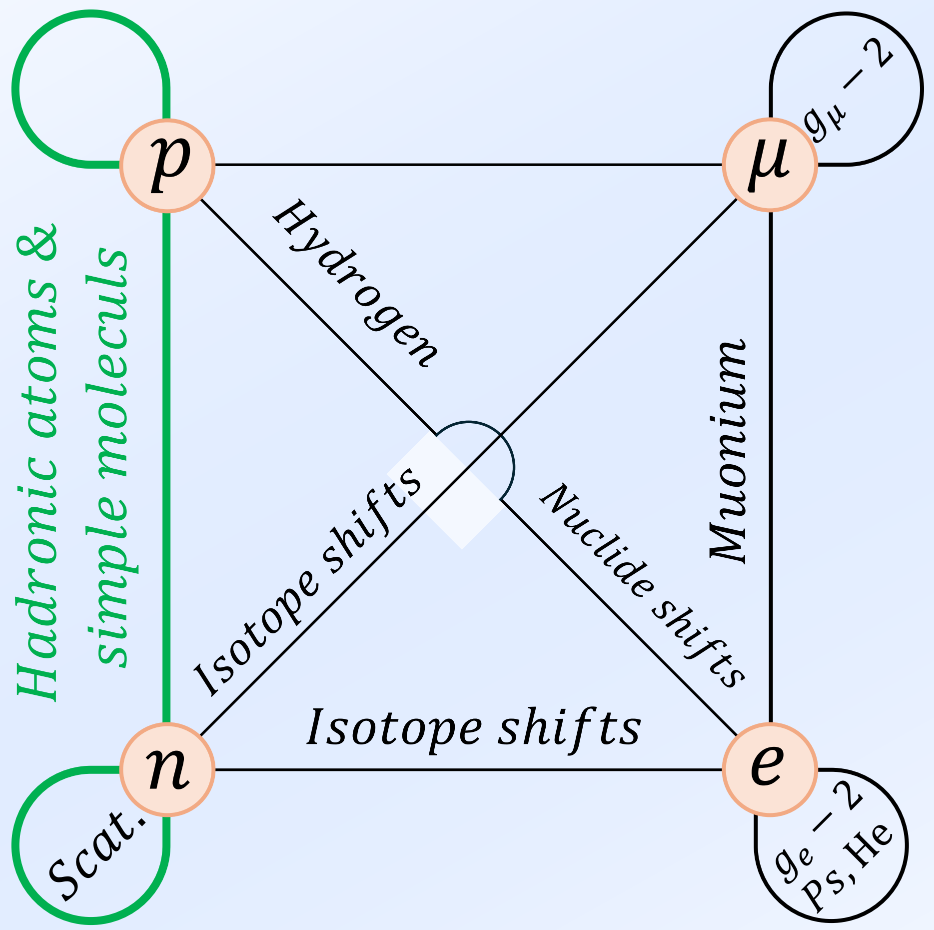
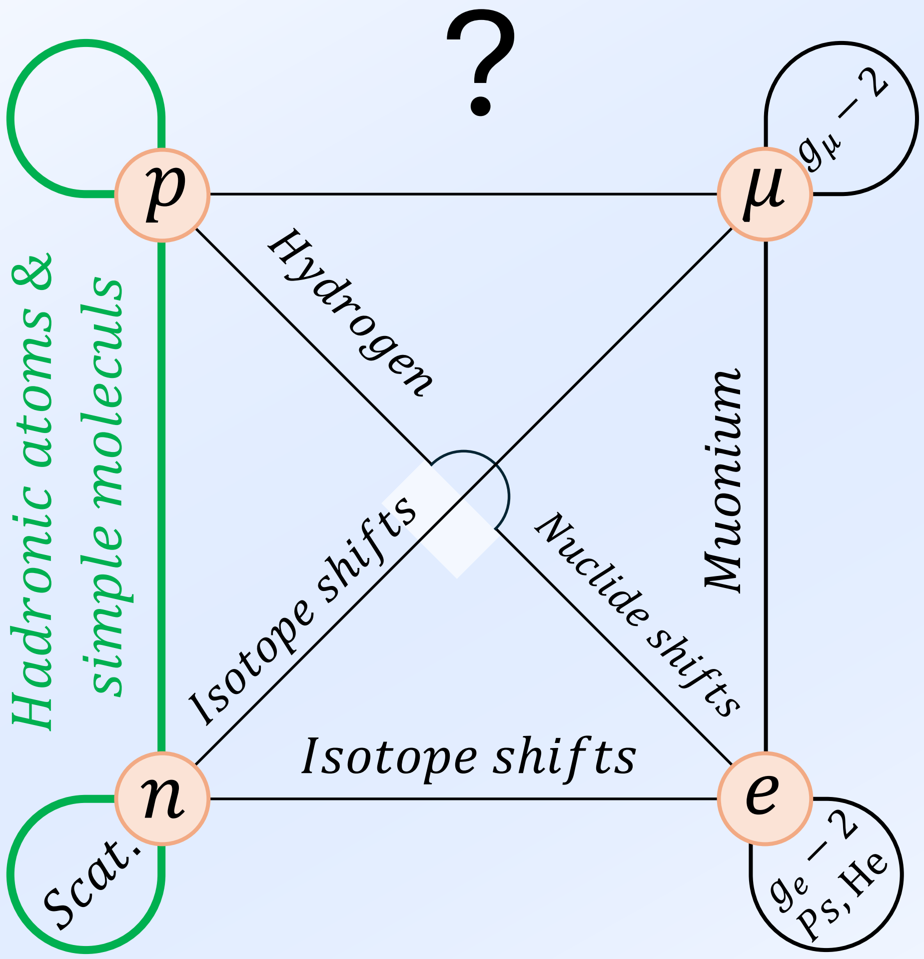


Panorama of heavy boson searches:



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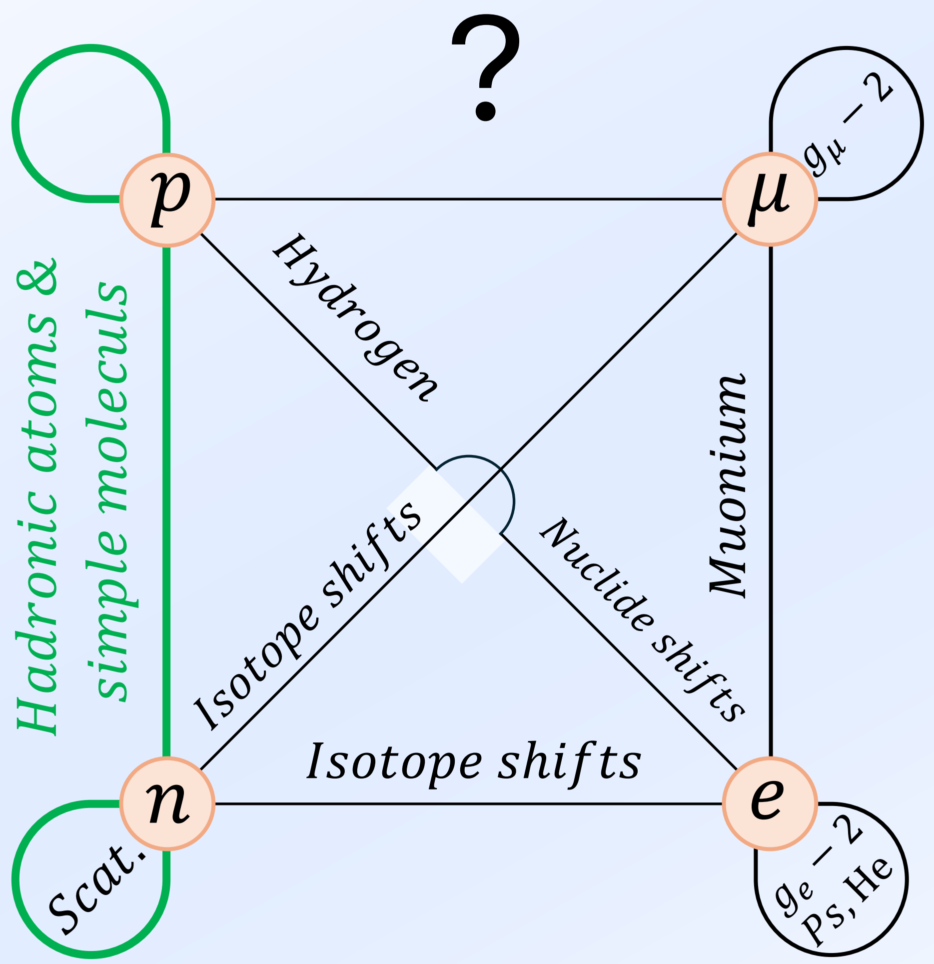
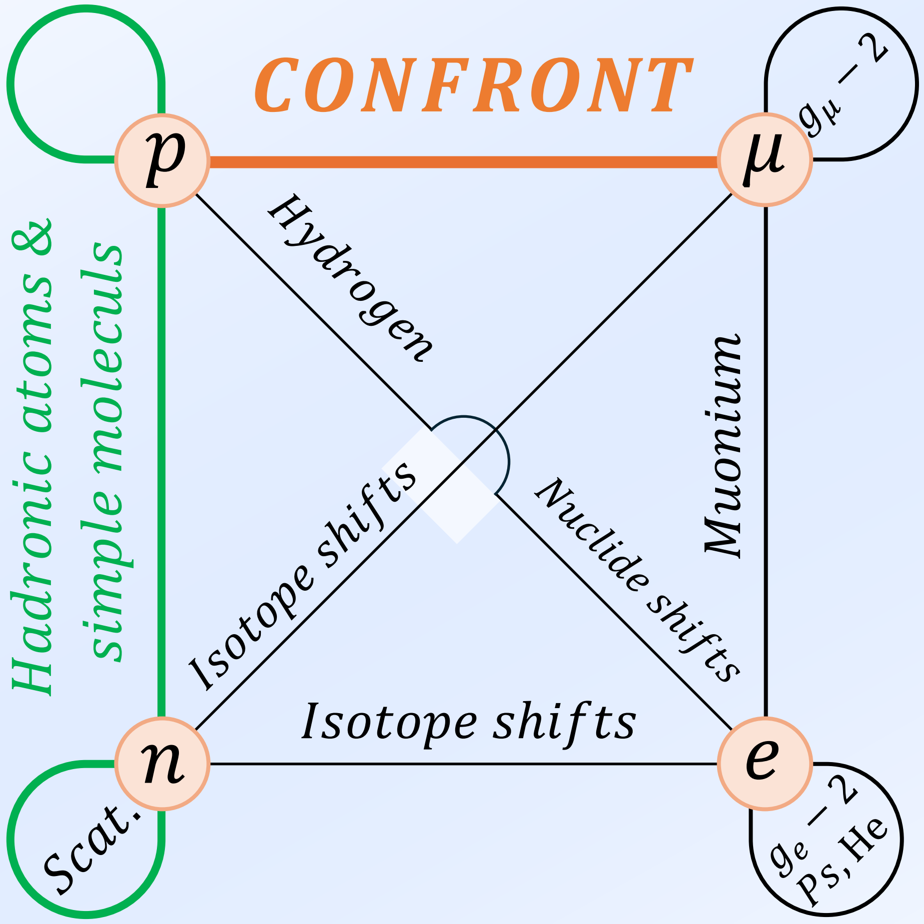


Need new experiments targeting contact-free transitions in muonic atoms !

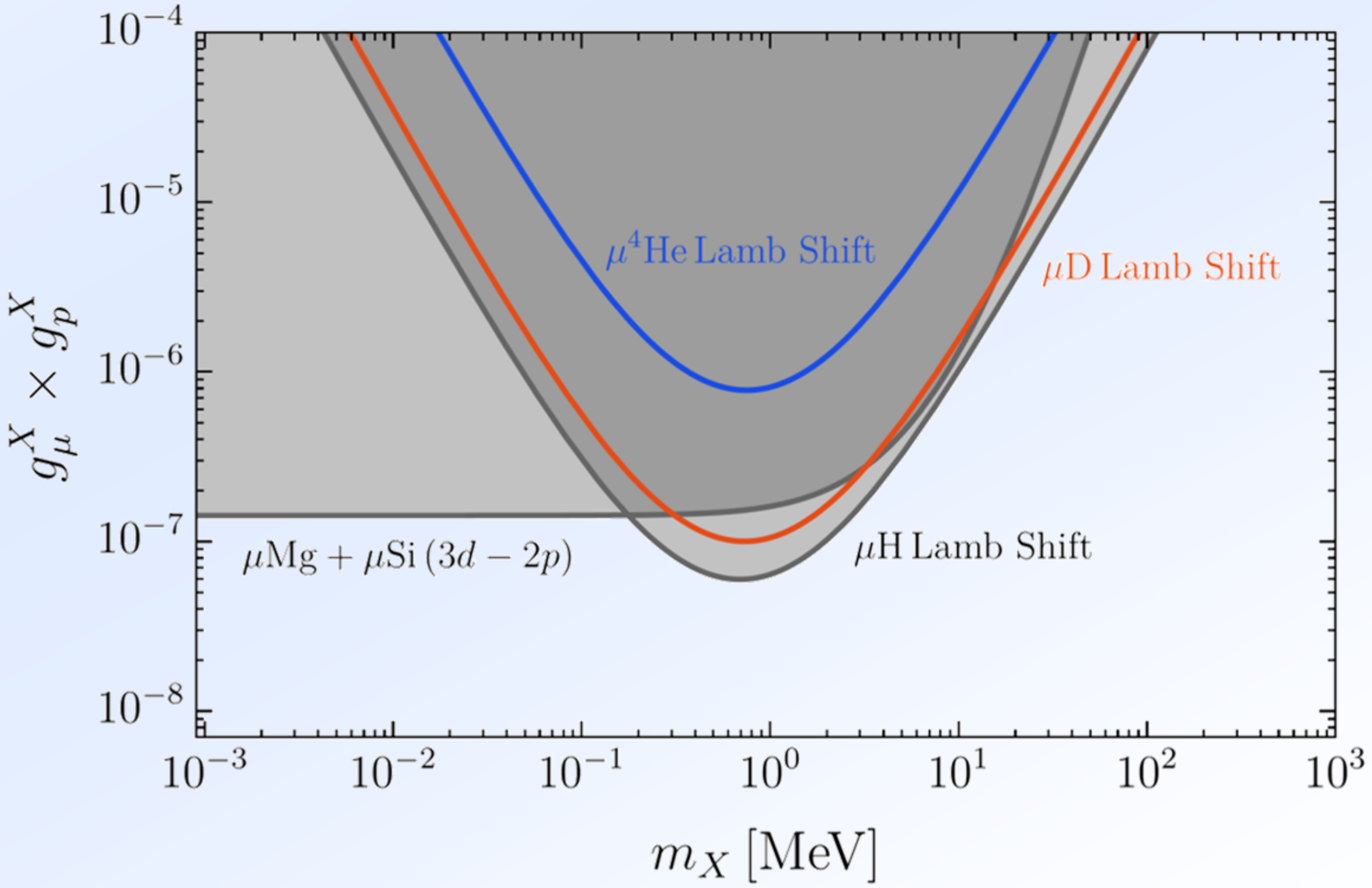
Panorama of heavy boson searches:



Contact – Free Muonic Atoms

Current bounds

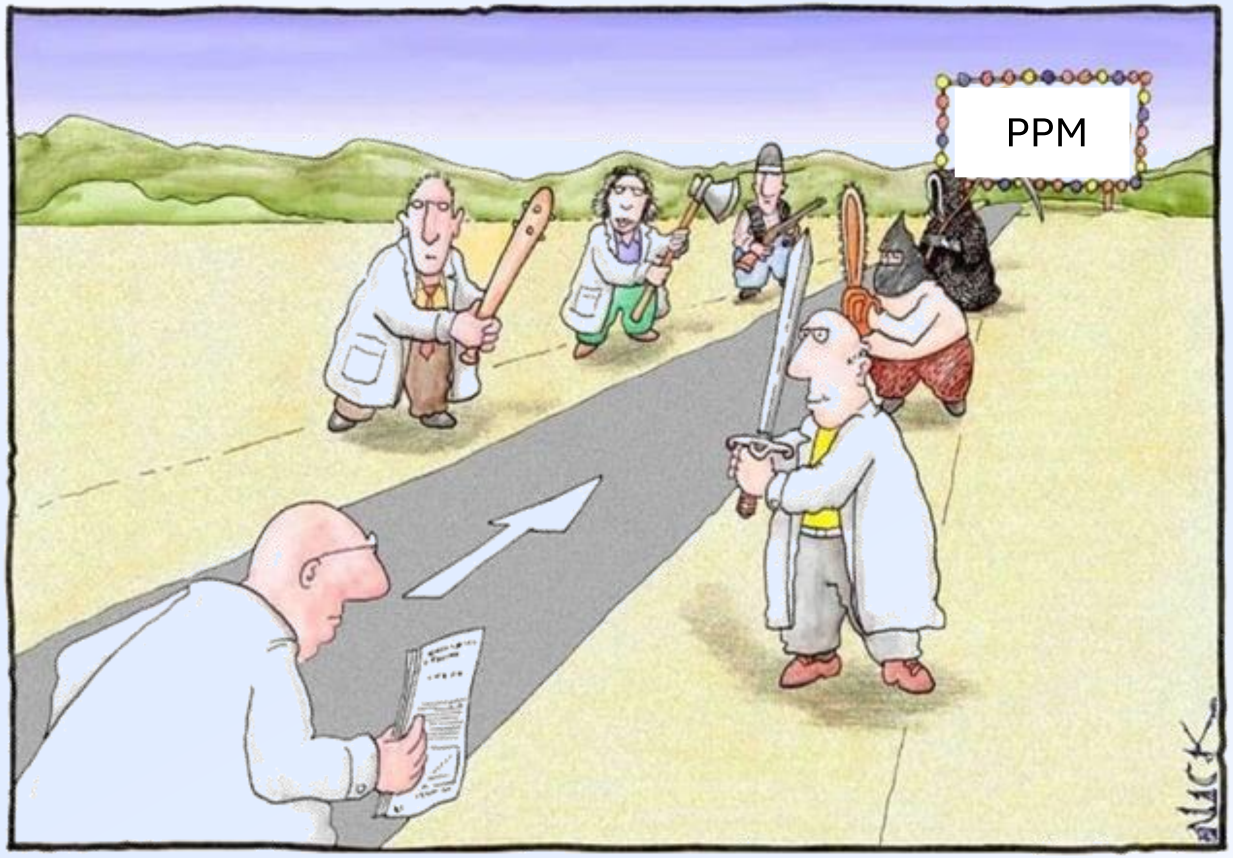
- Lamb shift measurements in muonic hydrogen, deuterium and helium (Randolf's talk) combined with radii from electronic atoms.
- have a complex interplay with fundamental constant determination and searched for new physics coupled to electrons. *Delaunay et. al.*
- Most straightforward bound from 3d-2p in μMg and μSi with combined 3 ppm accuracy.
- X-ray spectroscopy in the 1980's using crystal spectrometer. *Beltrami et. al.*
- (most?) stringent test of high field QED at twice the Schwinger limit
- There are also competitive bounds from heavier muonic atoms: arXiv:2512.16593



Can we do muonic atoms spectroscopy with ppm accuracy?

The road to PPM accuracy:

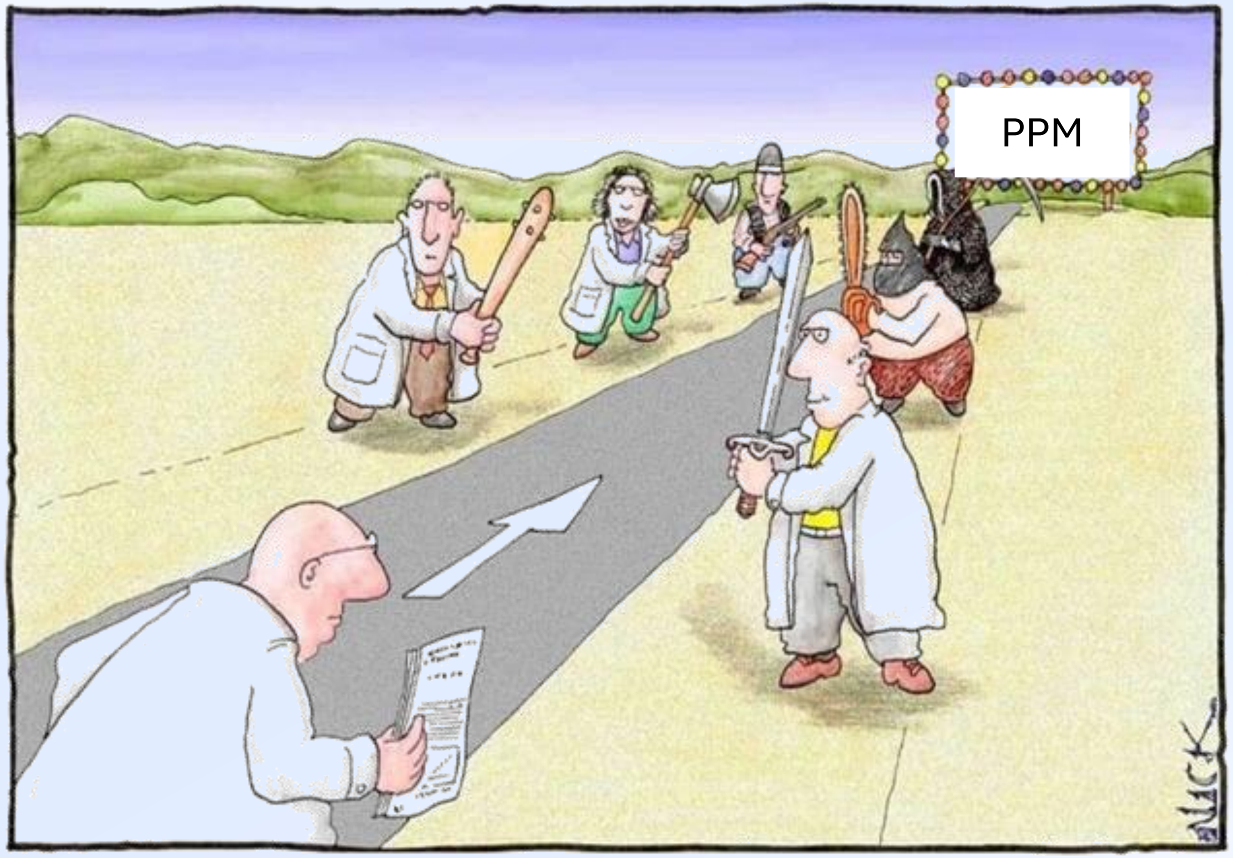
- Resolving power
- Lineshape
- Calibration



- Electron screening
- Pure QED
- Nuclear structure

The road to PPM accuracy:

- **Resolving power**
- Lineshape
- Calibration



- Electron screening
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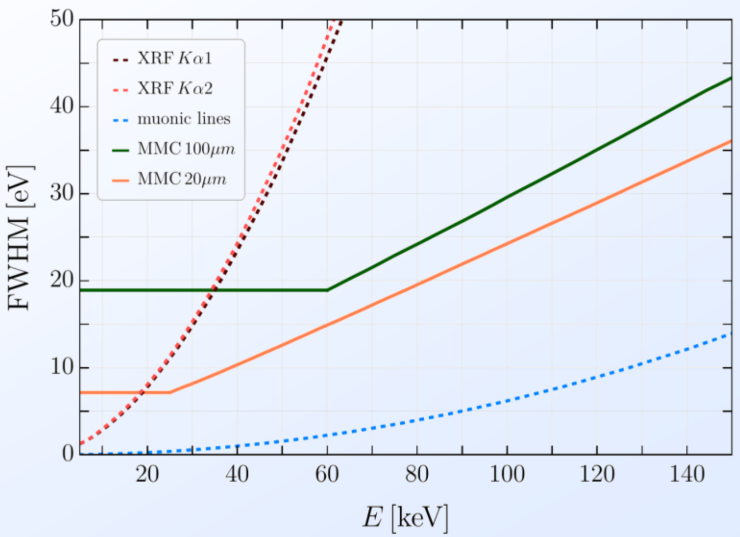
Feasibility study (Noam Burger, based on QUARTET data)

Resolution



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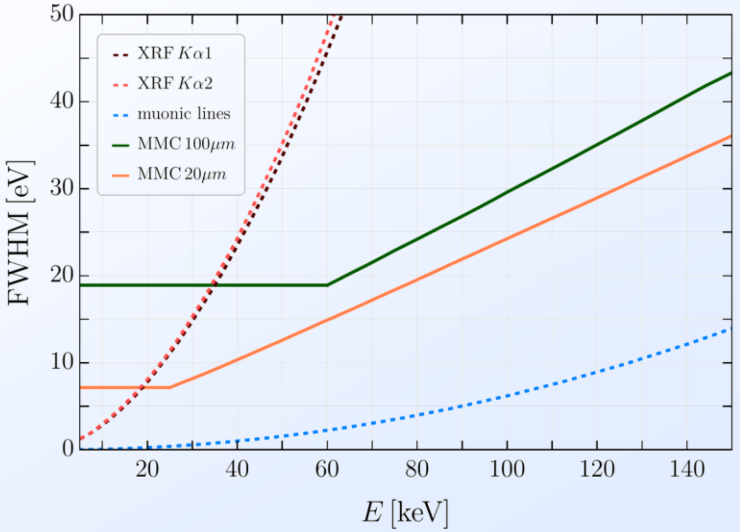
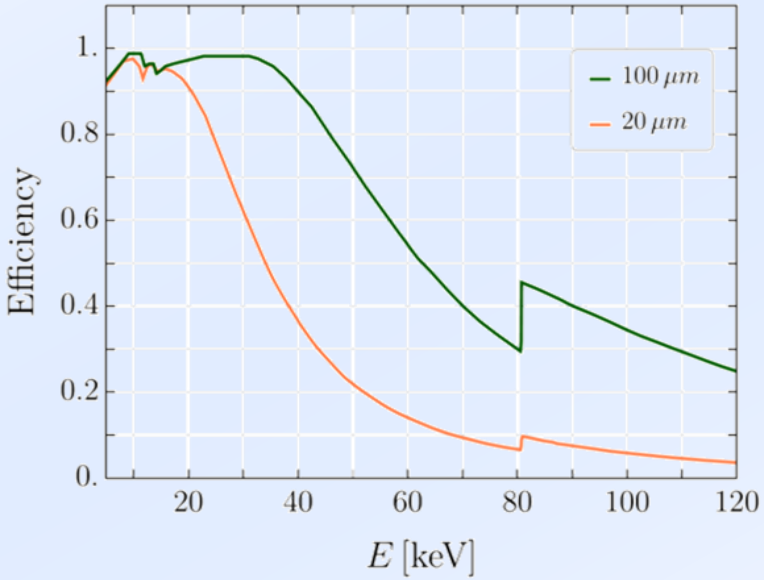


Quantum efficiency



+ solid angle of 10^{-4}

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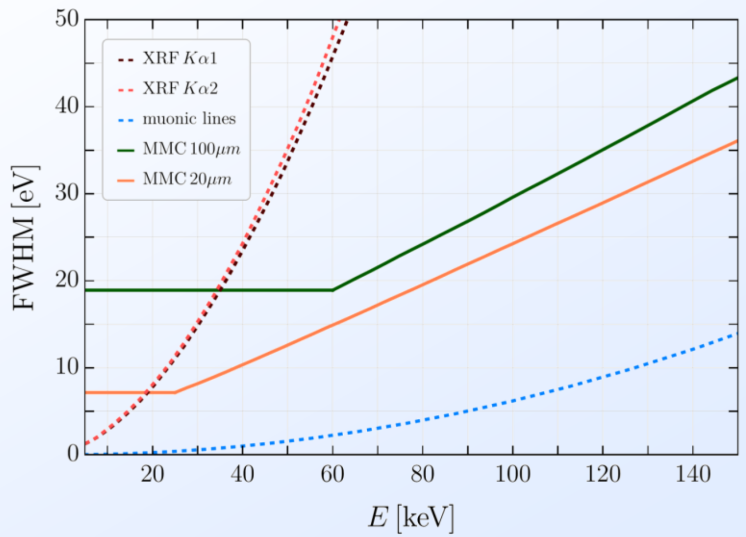

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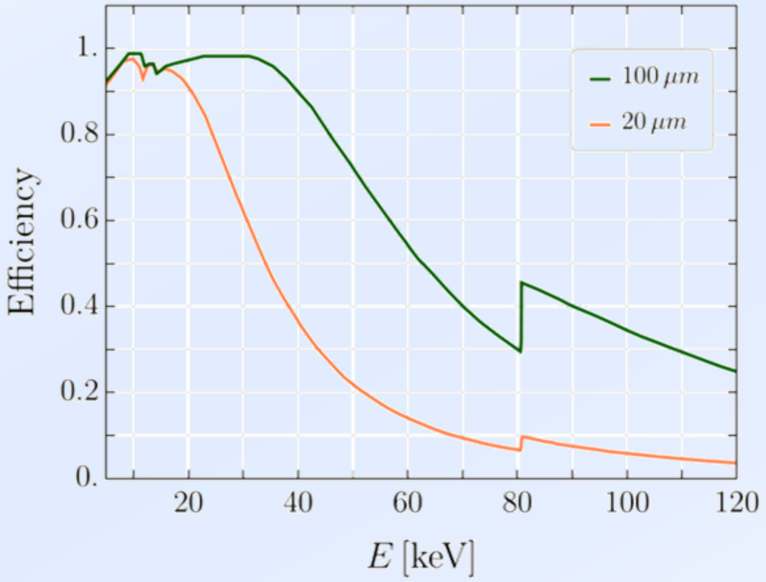
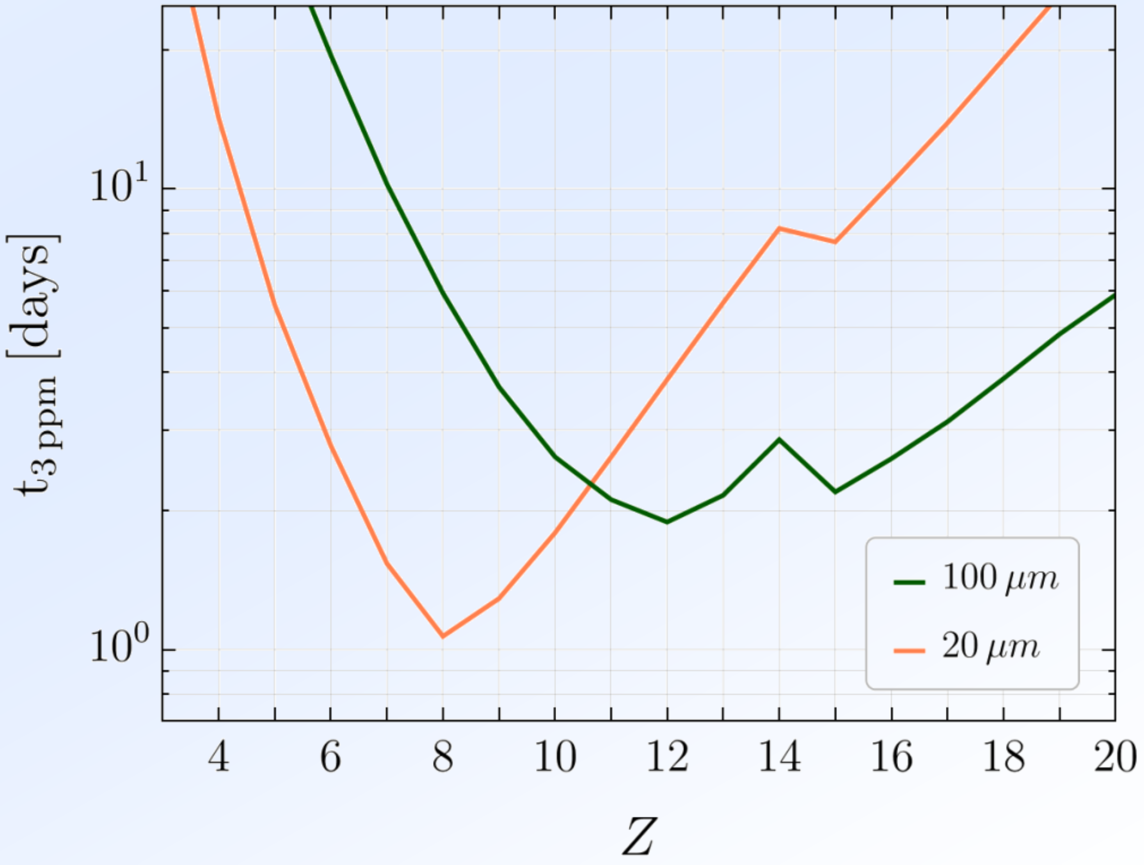


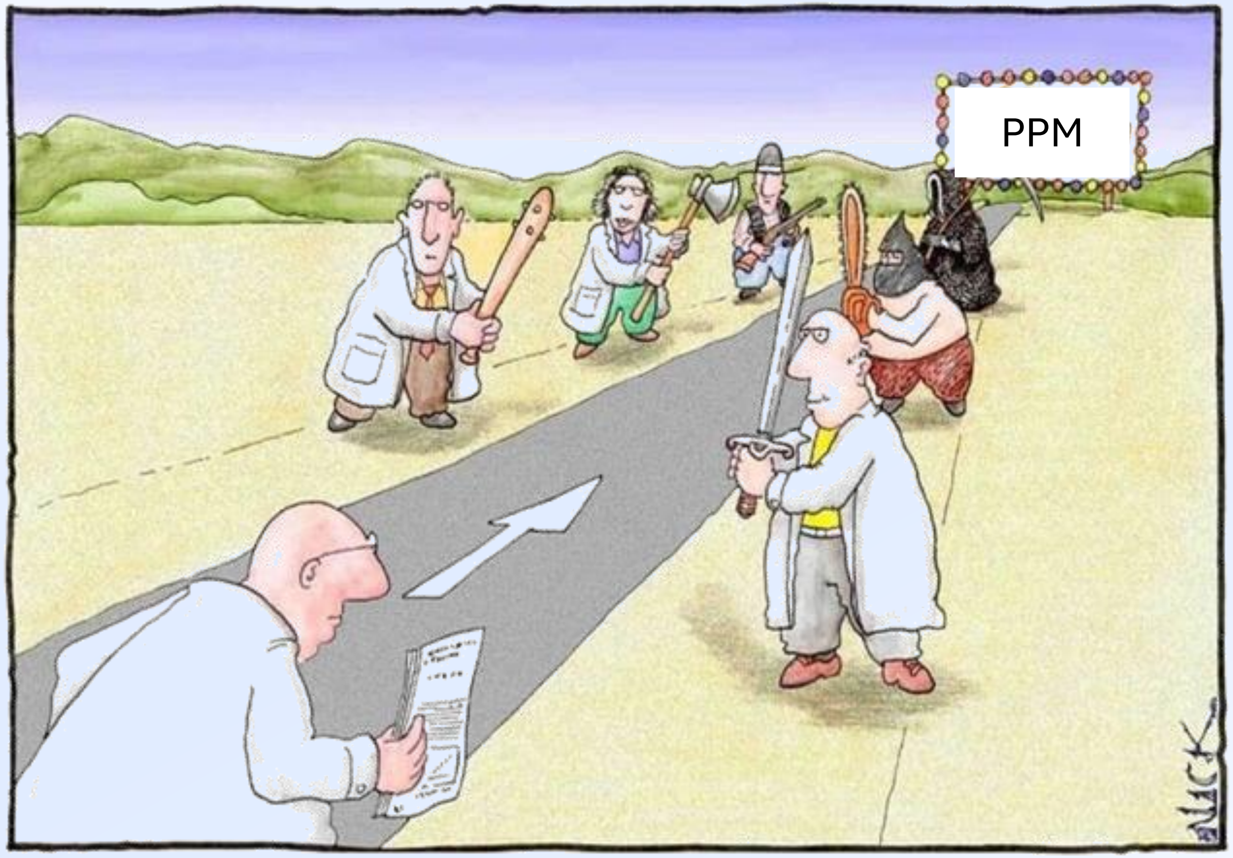
+ solid angle of 10^{-4}

Achievable precision



The road to PPM accuracy:

- Resolving power
- **Calibration**
- Lineshape



- Electron screening
- Pure QED
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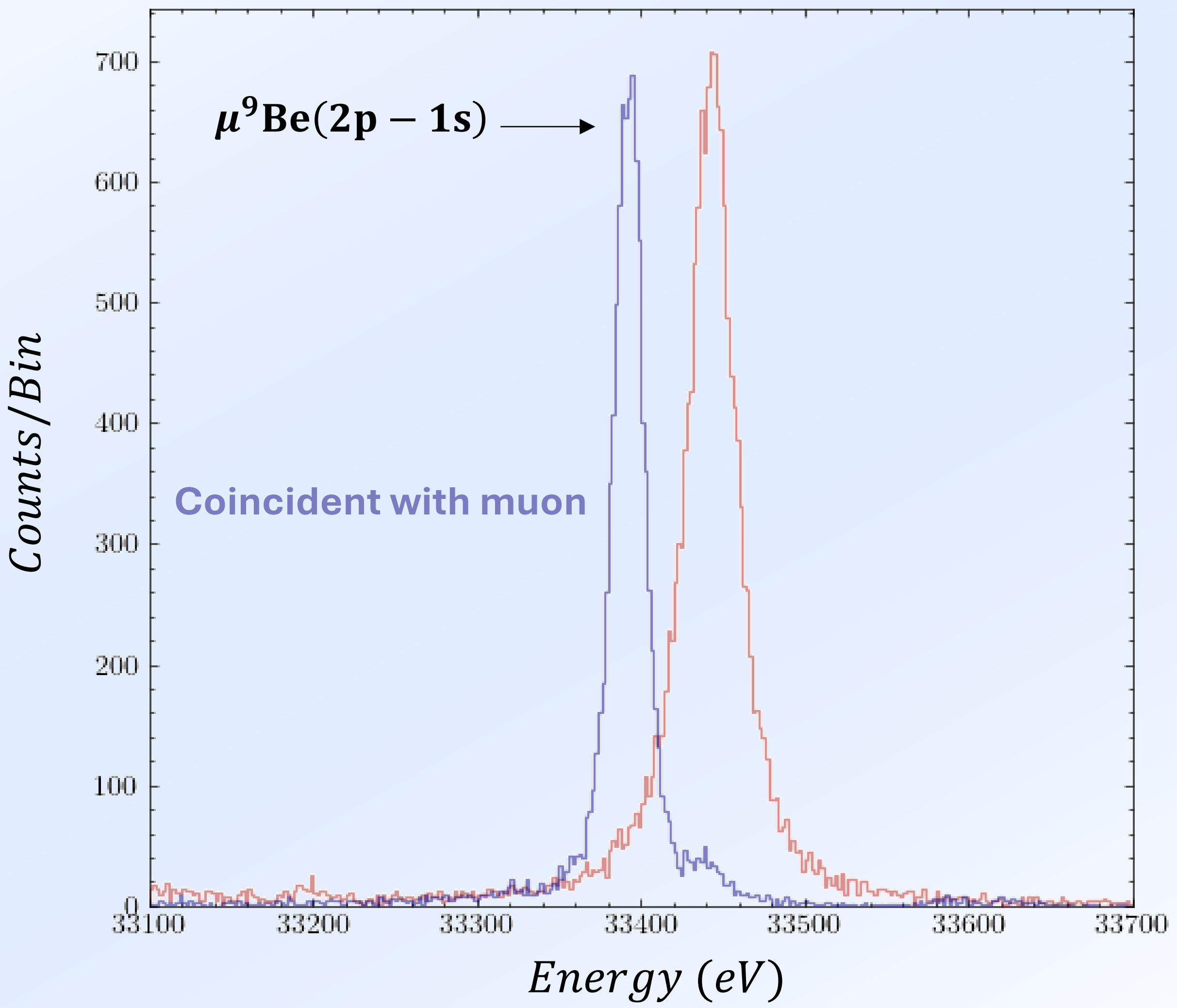
What we mean by calibration :



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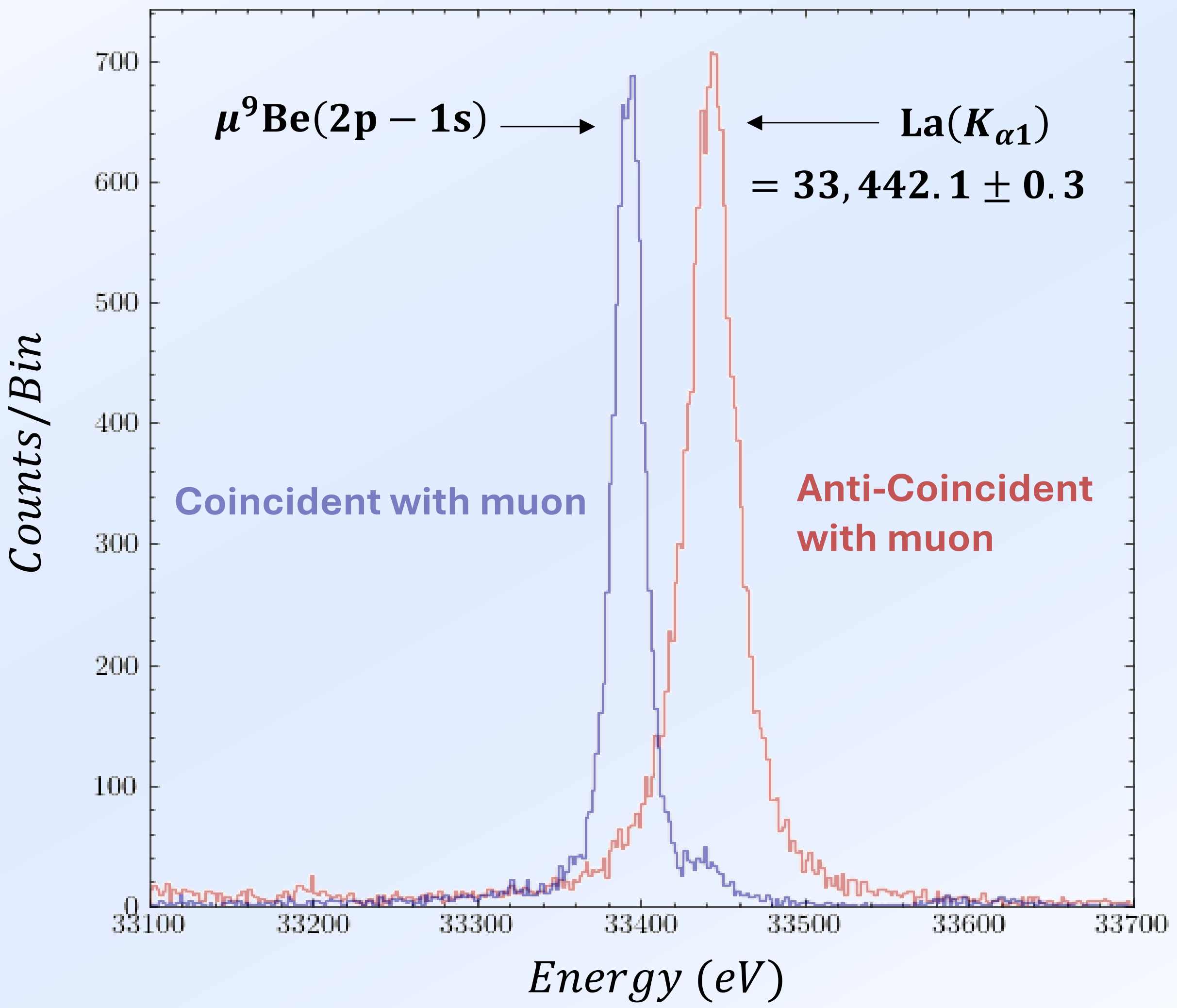

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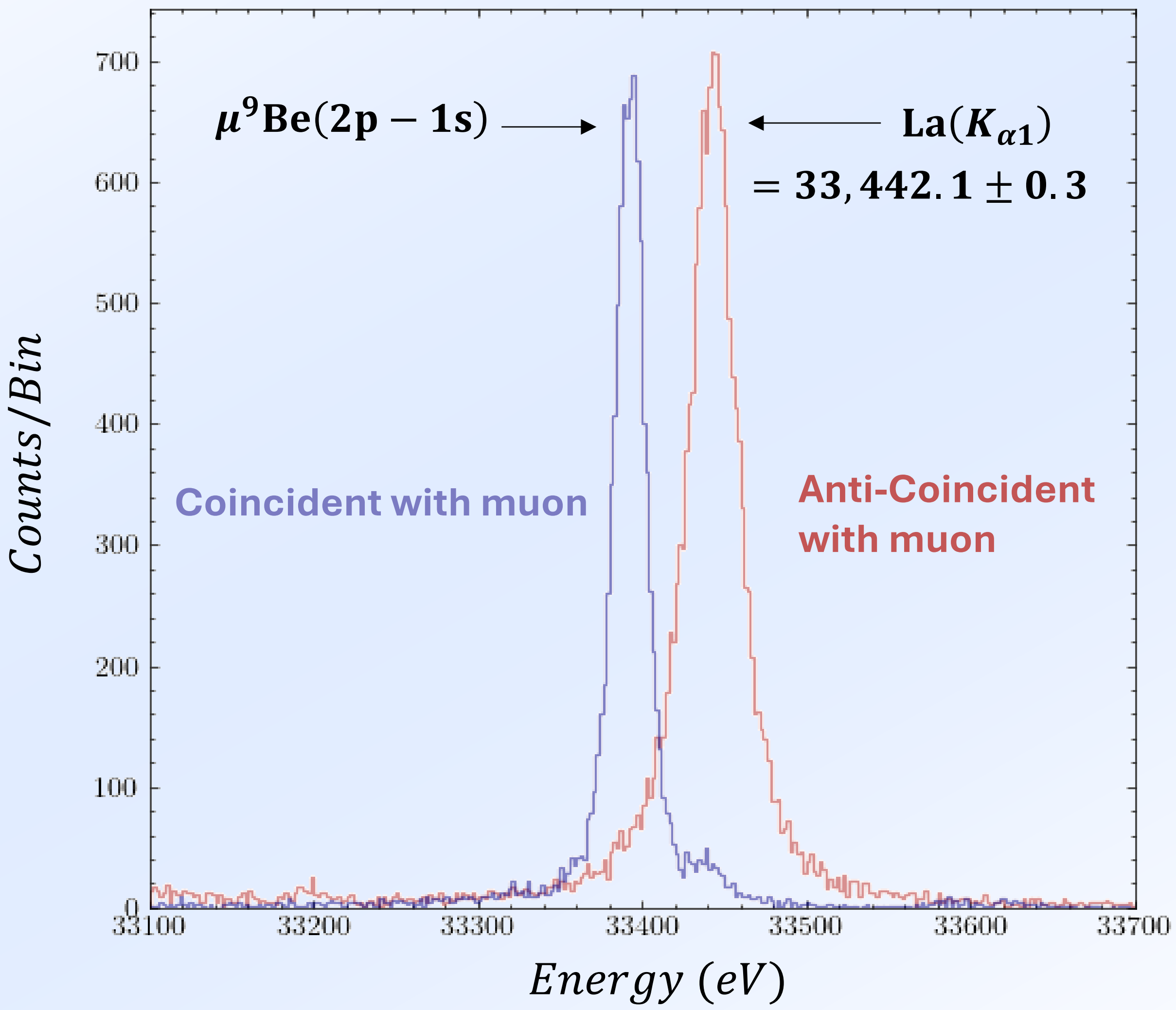
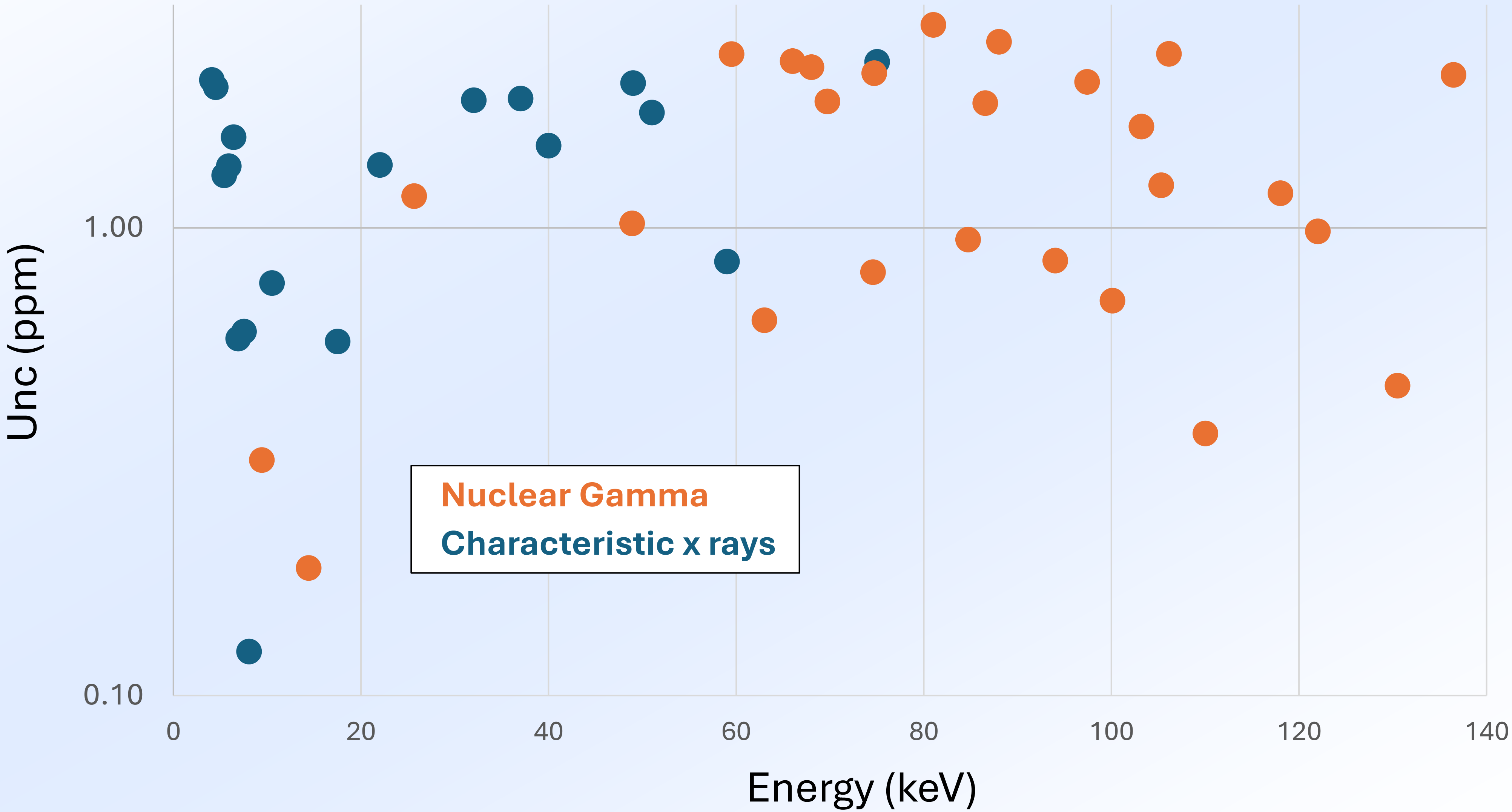


Muonic energy =
difference to calibration +
literature value of calibration

Calibration lines with sub ppm uncertainty are **rare** and **far between**



“Literature” values are not static !

arXiv:2602.12836

Measurements of absolute gamma-ray energies using an ultra-high energy resolution magnetic microcalorimeter

Matias Rodrigues[1], Mostafa Lokman Zahir[1], Martin Loidl[1], Lucille Chambon[1], Quentin Drenne[1], Michael Müller[2], Sebastian Kempf[2,3], Etienne Nigron[4] and Ferid Haddad[4,5]

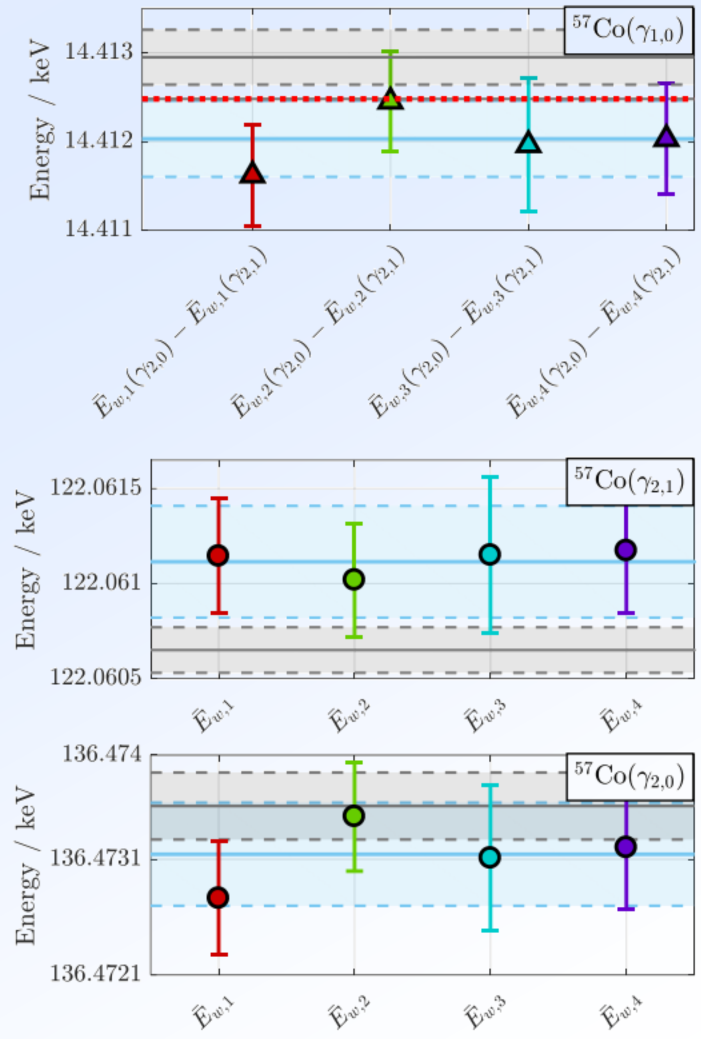
[1]Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120 Palaiseau, France

[2]Institute of Micro- and Nanoelectronic Systems (IMS), Karlsruhe Institute of Technology (KIT), Hertzstrasse 16, 76187 Karlsruhe, Germany.

[3]Institute for Data Processing and Electronics (IPE), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany.

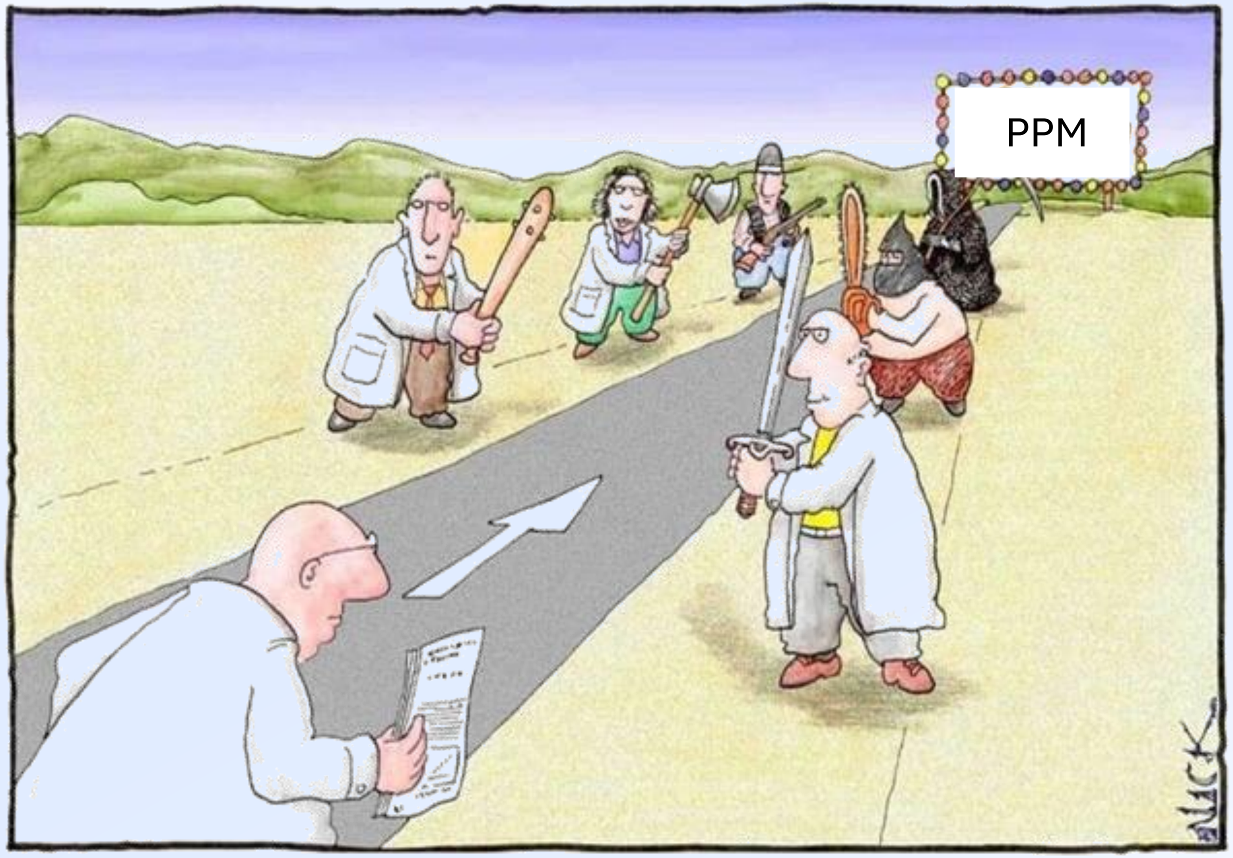
[4]GIP ARRONAX, 1 rue Aronnax, CS10112, 44817 Saint-Herblain Cedex, France

[5]Laboratoire Subatech, UMR 6457, IMT Nantes Atlantique/CNRS-IN2P3/Nantes, France



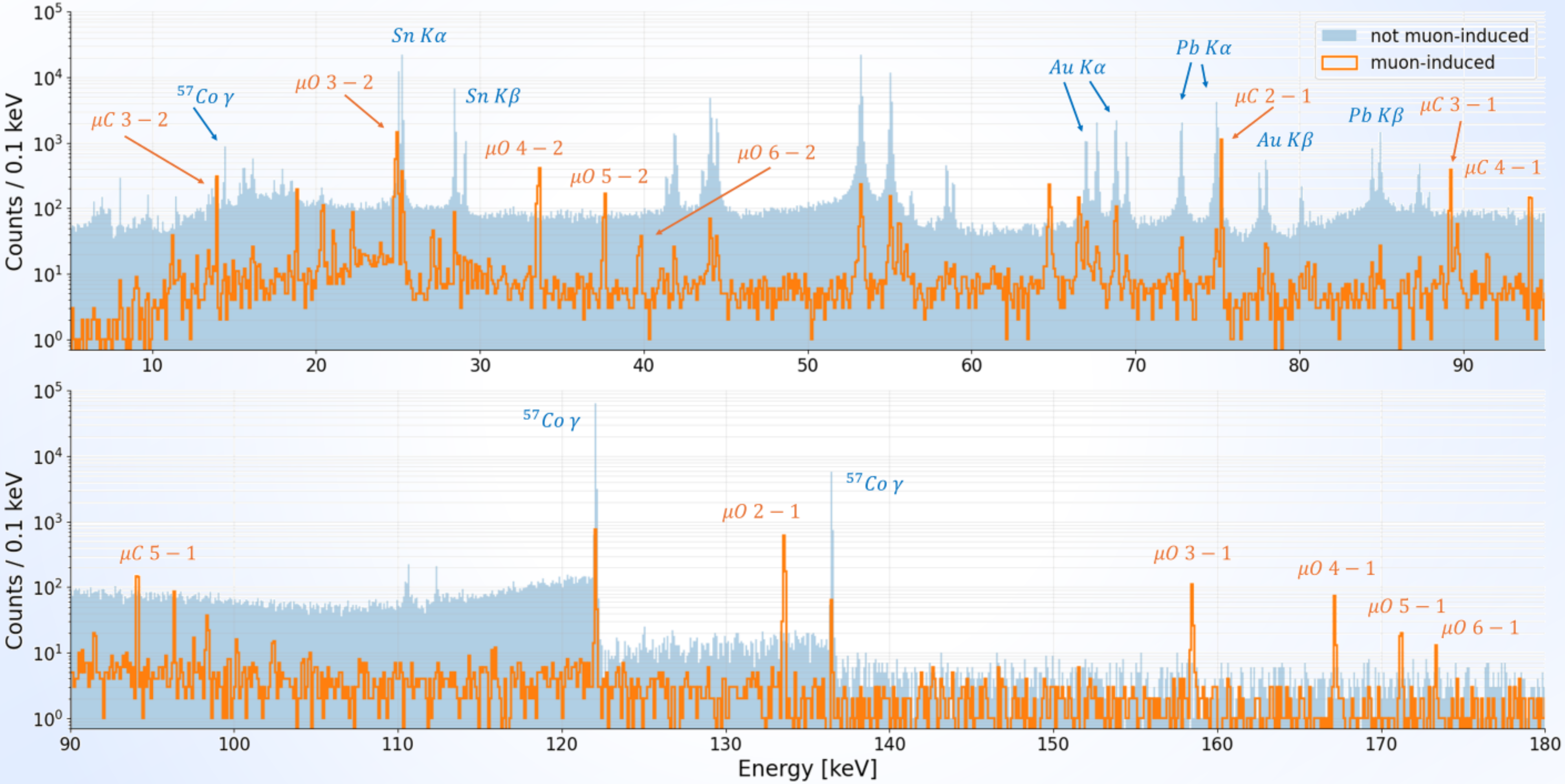
The road to PPM accuracy:

- Resolving power
- Calibration
- **Lineshape**



- Electron screening
- Pure QED
- Nuclear structure

Preliminary results in muonic enriched Oxygen



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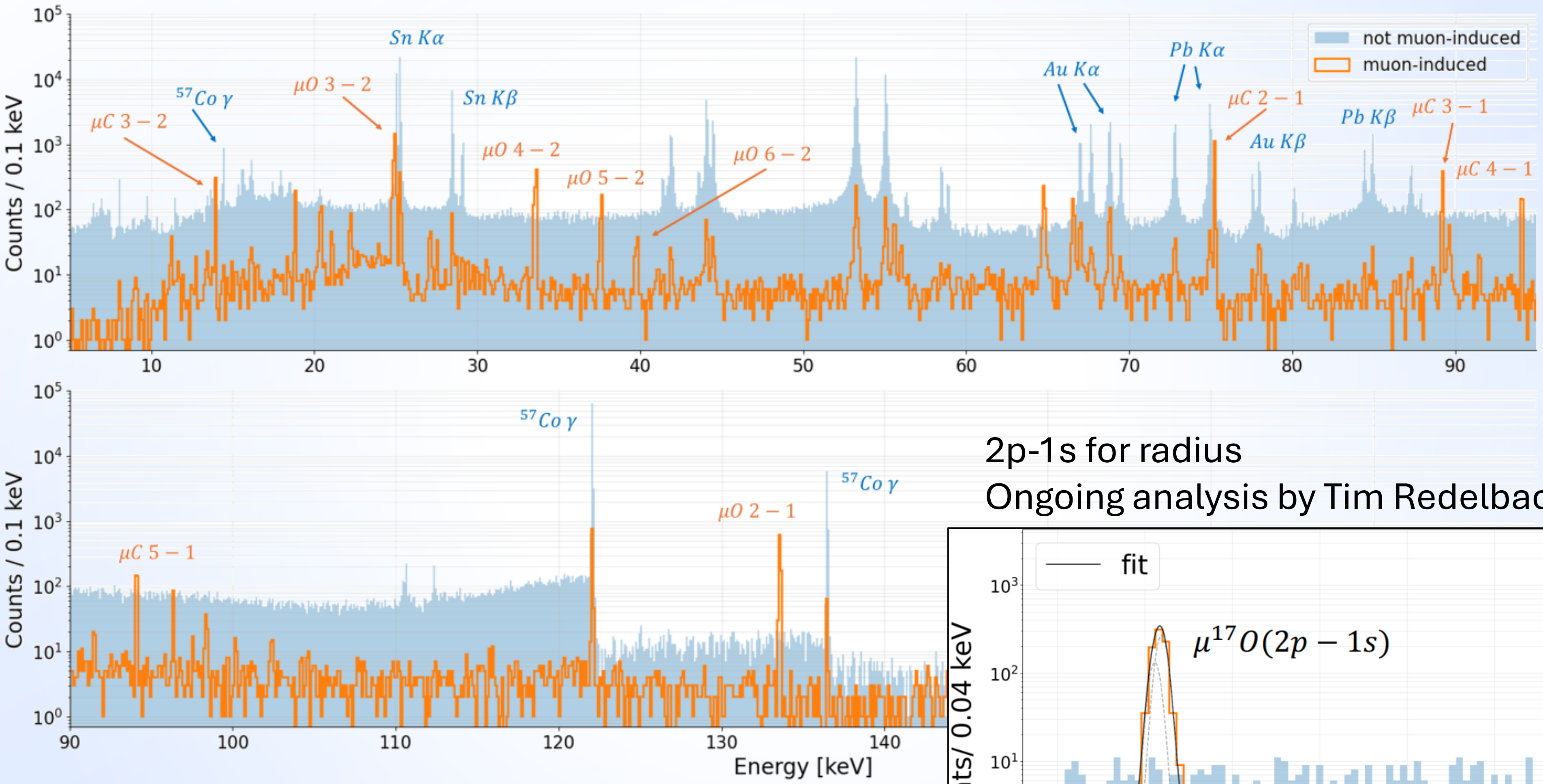
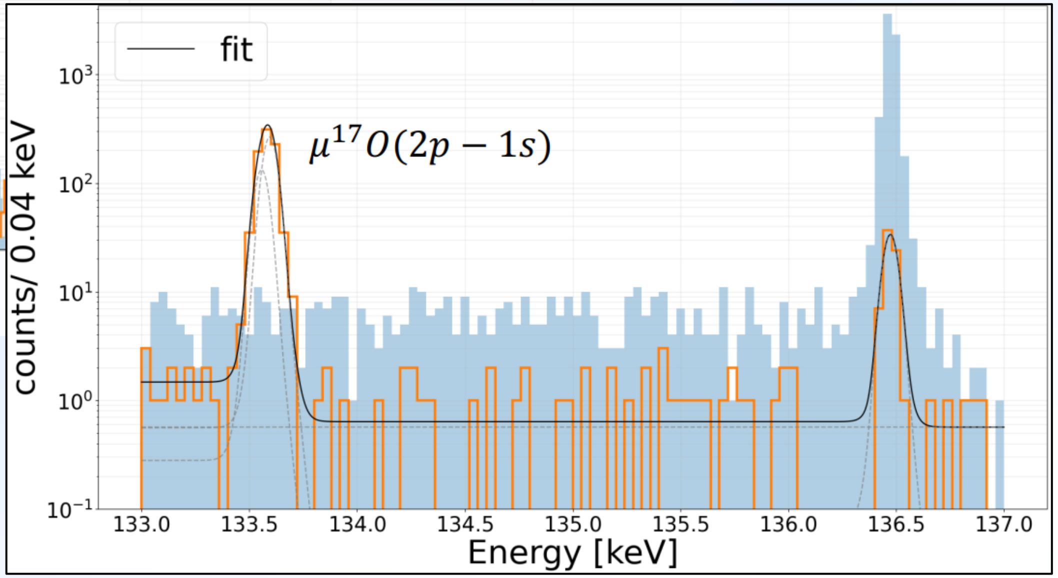


2p-1s for radius
Ongoing analysis by Tim Redelbach (Mainz)



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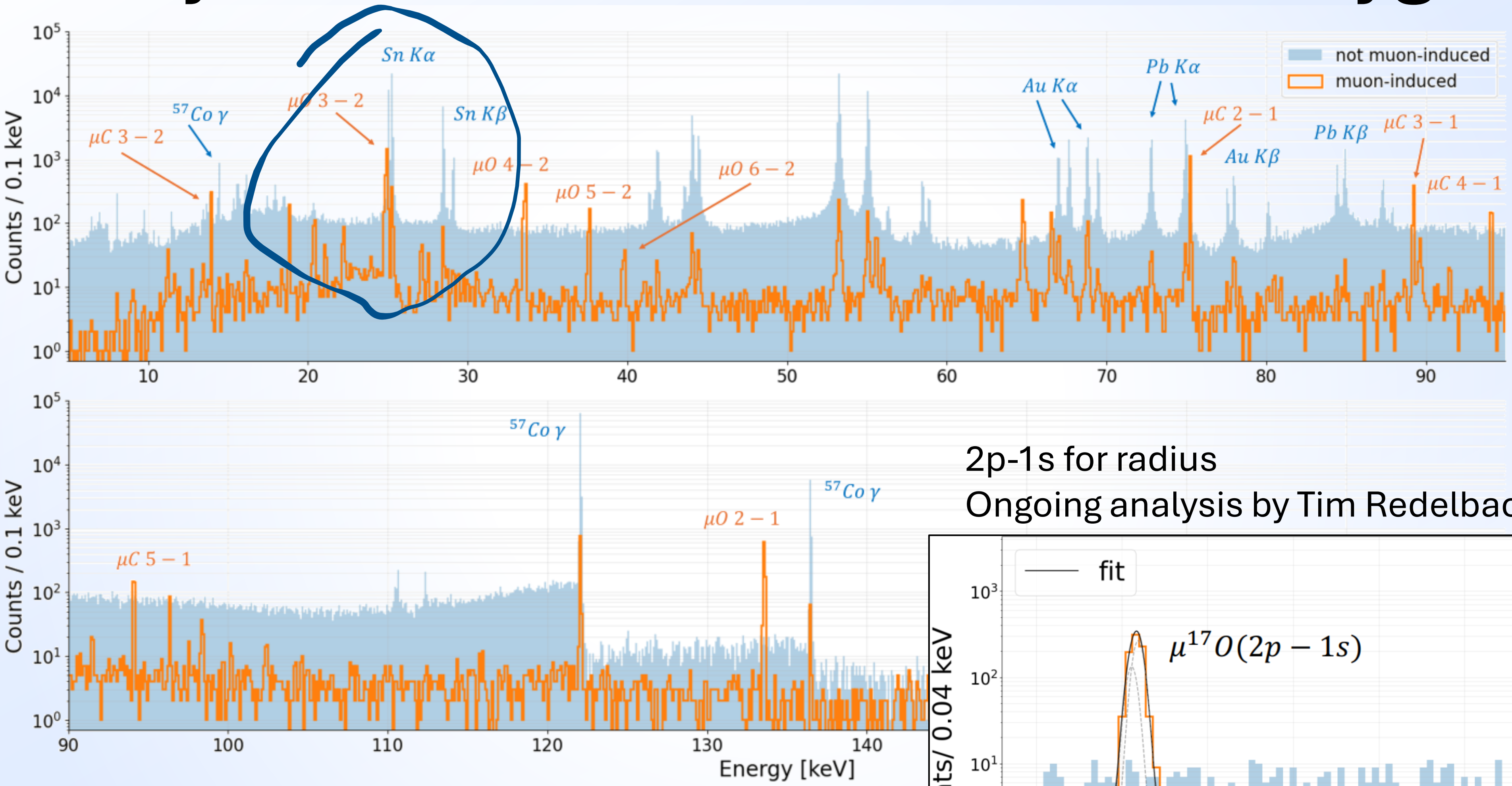

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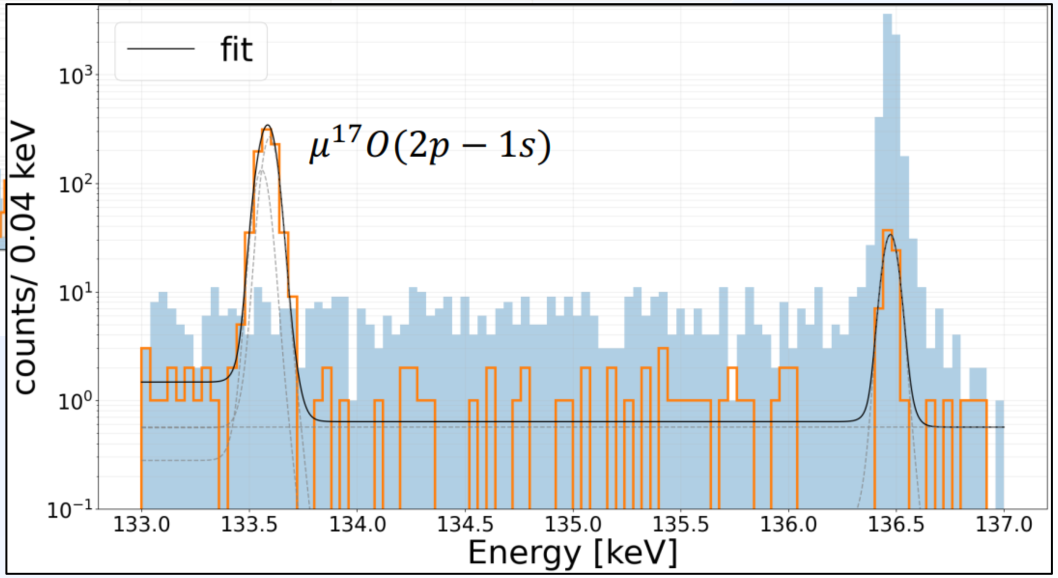
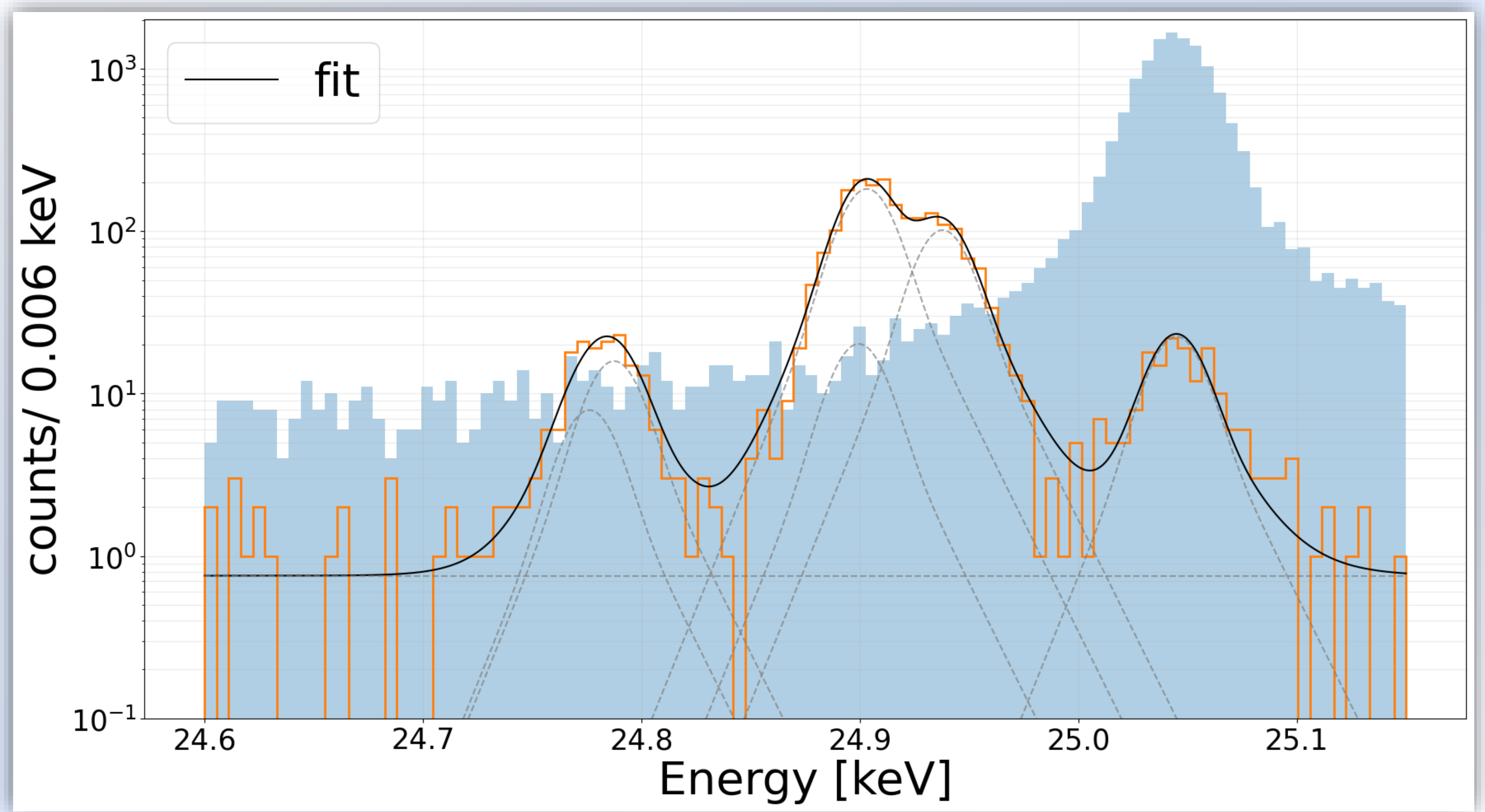


First 3-2 spectrum in $\mu^{17}O$

$Sn\ (K\alpha)$



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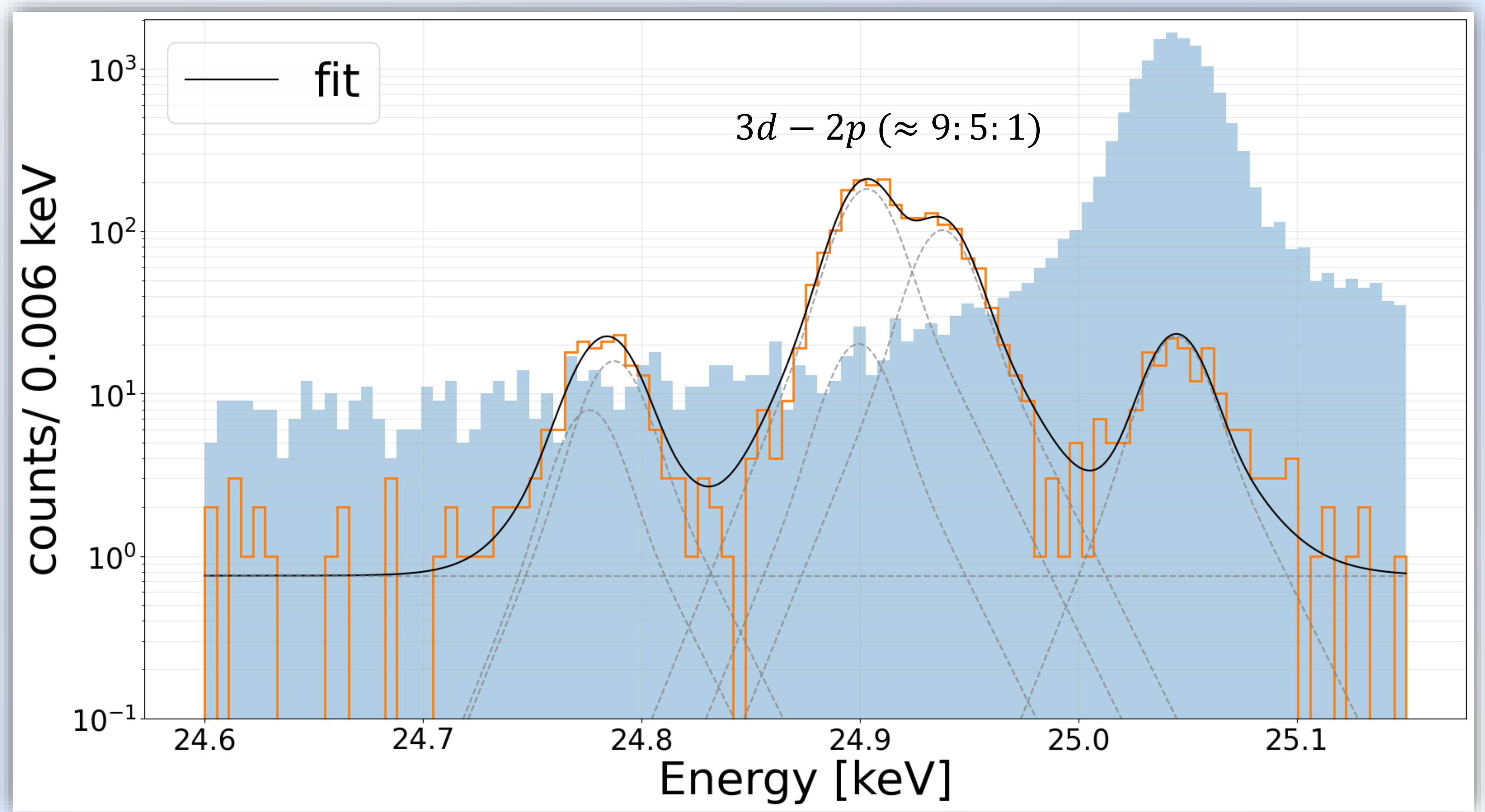

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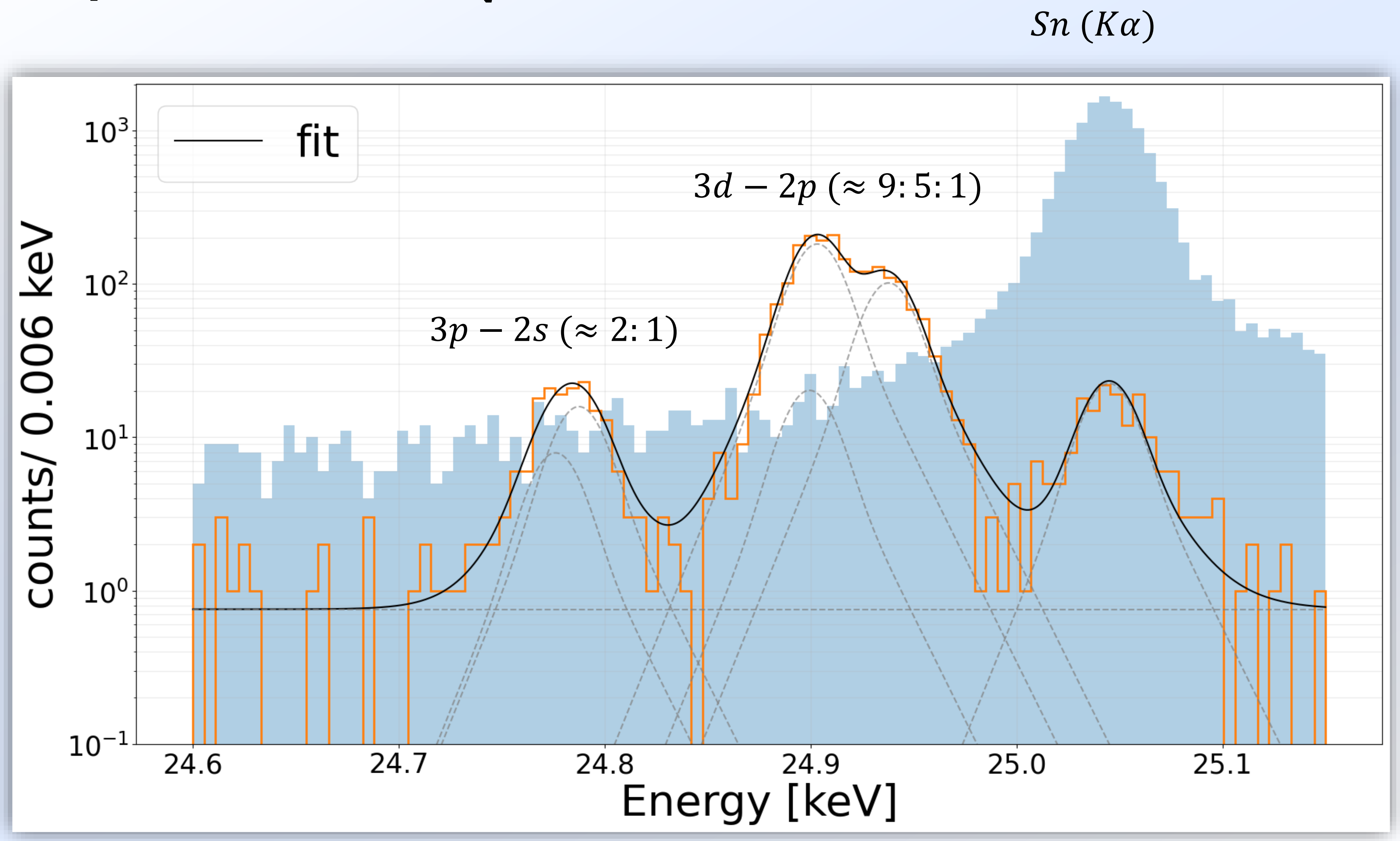

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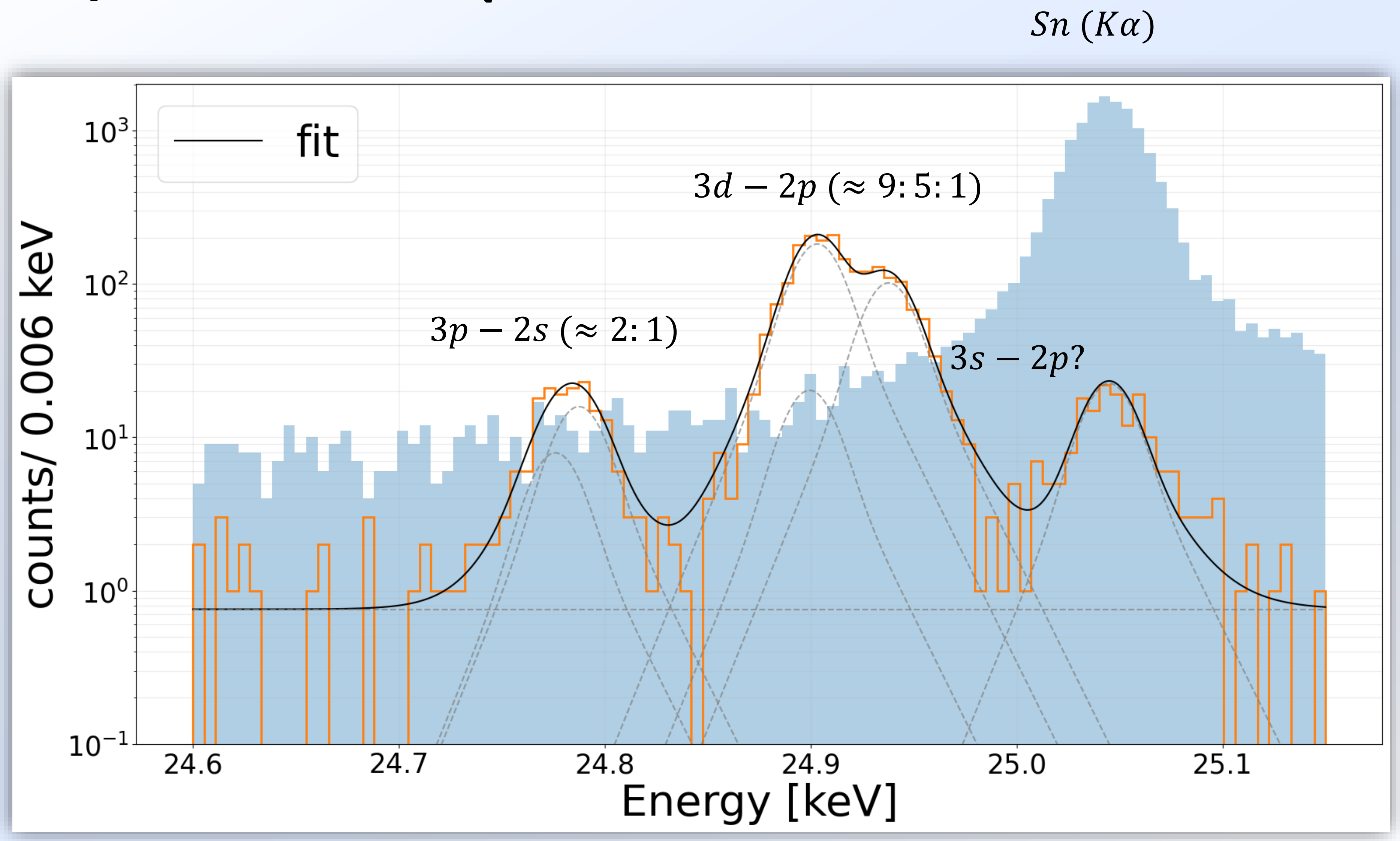

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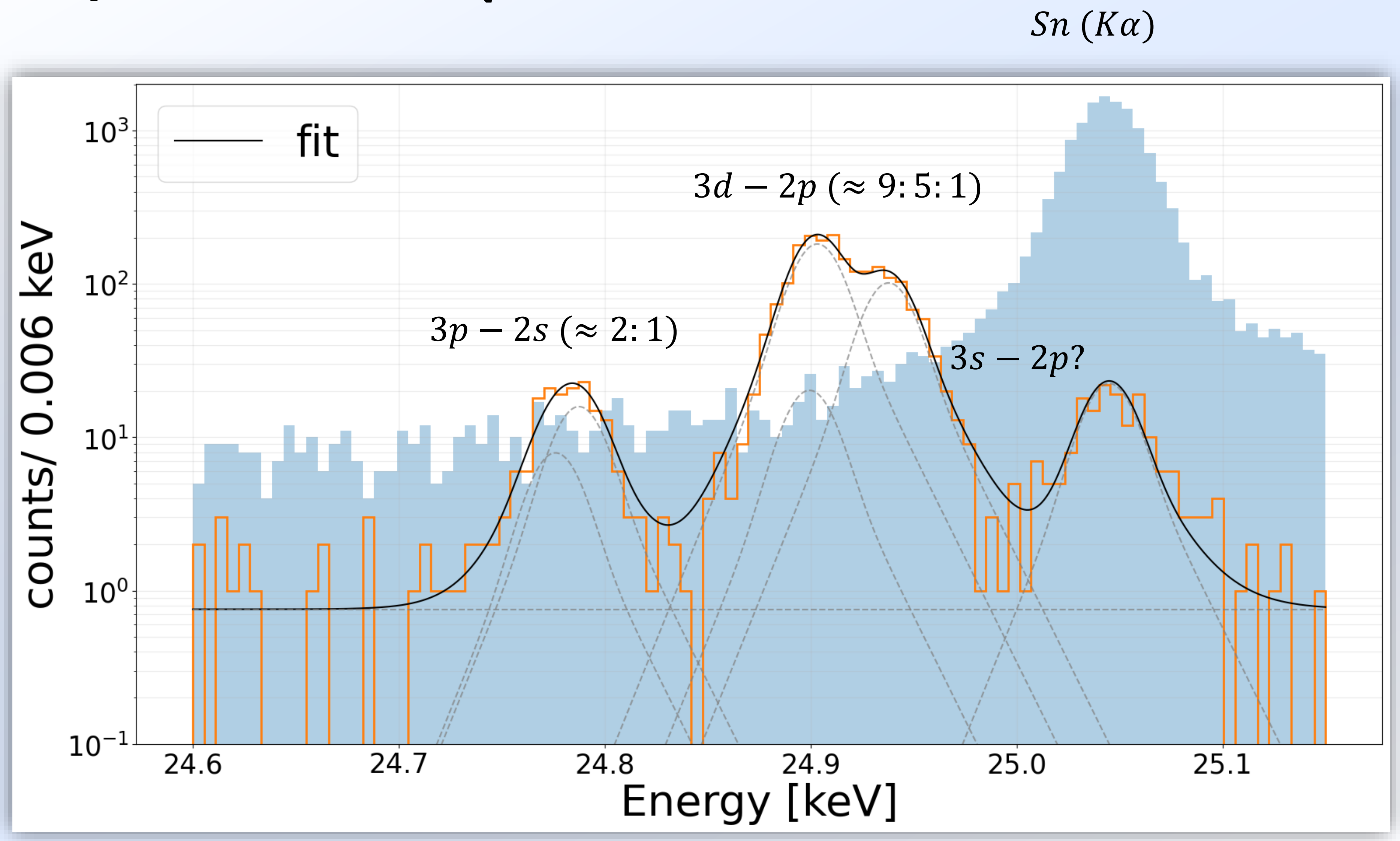
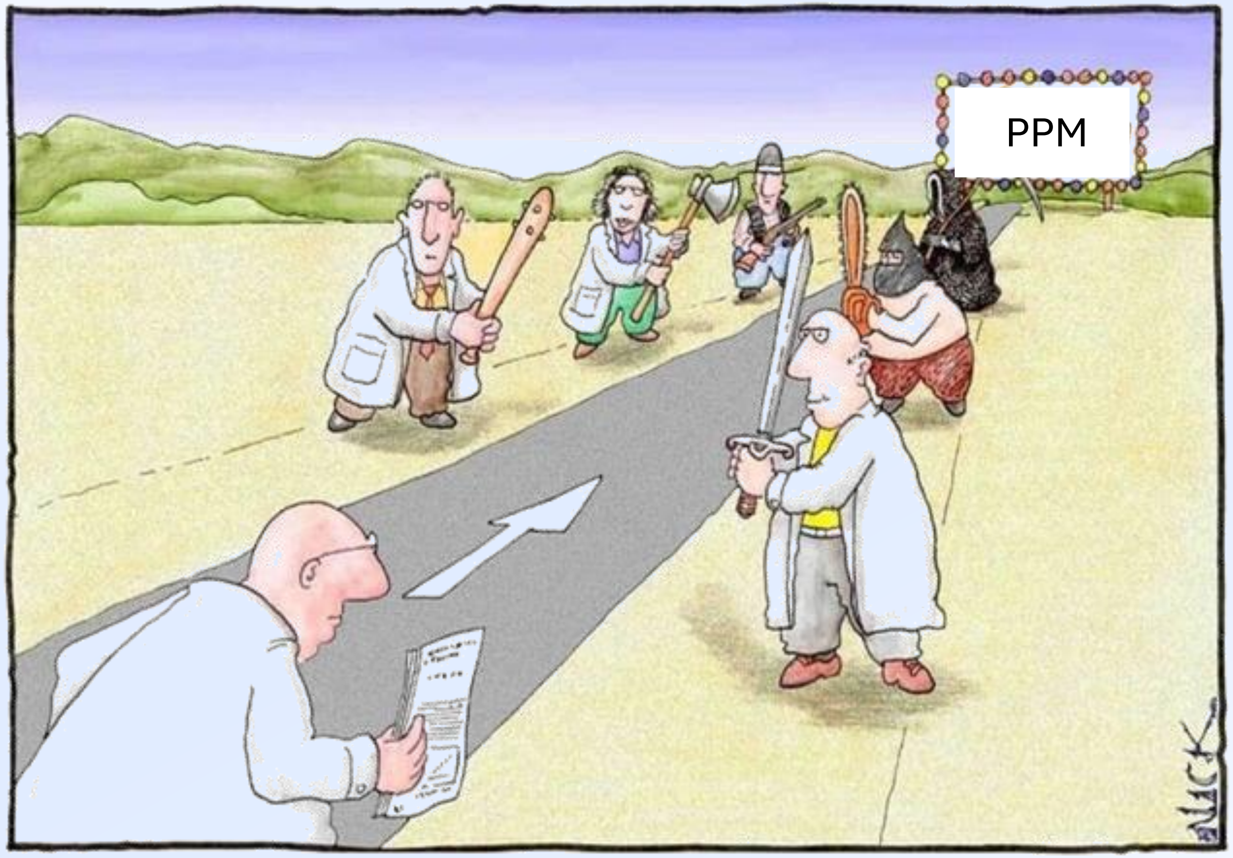


Need broad experimental program to study linesahapes

The road to PPM accuracy:

- Resolving power
- Lineshape
- Calibration



- **Electron screening**
- Pure QED
- Nuclear structure

Electron screening shifts

- Residual electrons shift muonic atom energies.
- Can we (by *we* I mean *you*) calculate them ?
- Preliminary results from Sergiy Bubin
- Even if, can we predict the average population?

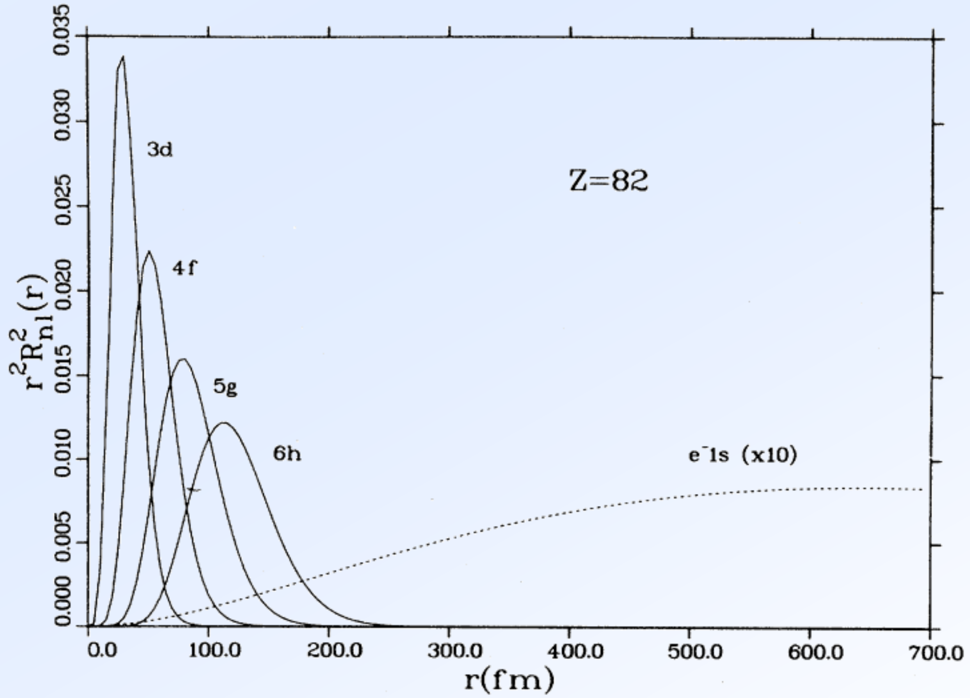


FIG. 1. Muon wave functions (solid lines) for relatively high-lying states, compared to the electron 1*s* wave function (dashed line).

Rev. Mod. Phys., Vol. 54, No. 1, January 1982

Low Z gas targets

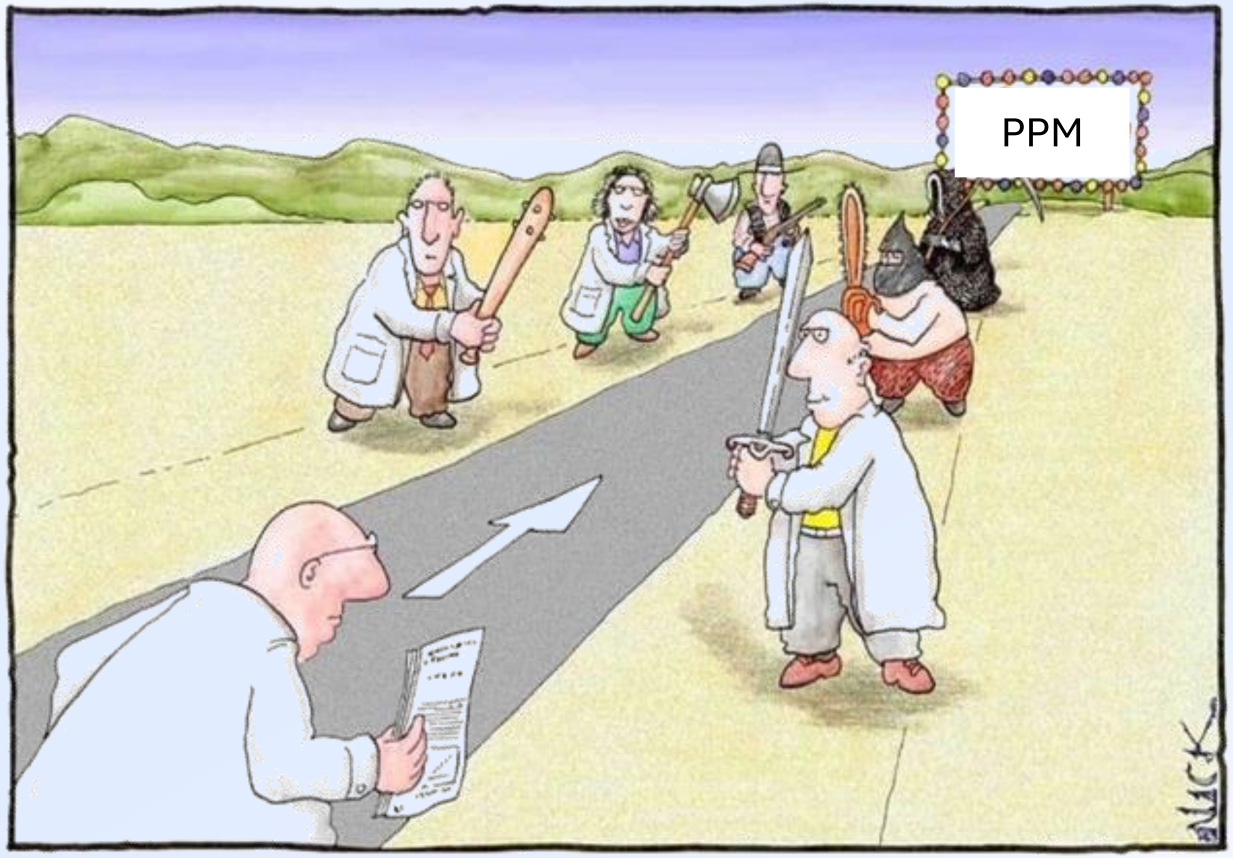
- No remaining electrons
- Molecular explosion broadening
- Poor stopping power
- Difficulty in working with isotopically enriched targets

Solid/Liquid targets

- Can efficiently stop muons
- Use and reuse isotopically enriched targets
- More x-ray absorption
- Unclear how many electrons remain

The road to PPM accuracy:

- Resolving power
- Lineshape
- Calibration



- Electron screening
- **Pure QED**
- Nuclear structure

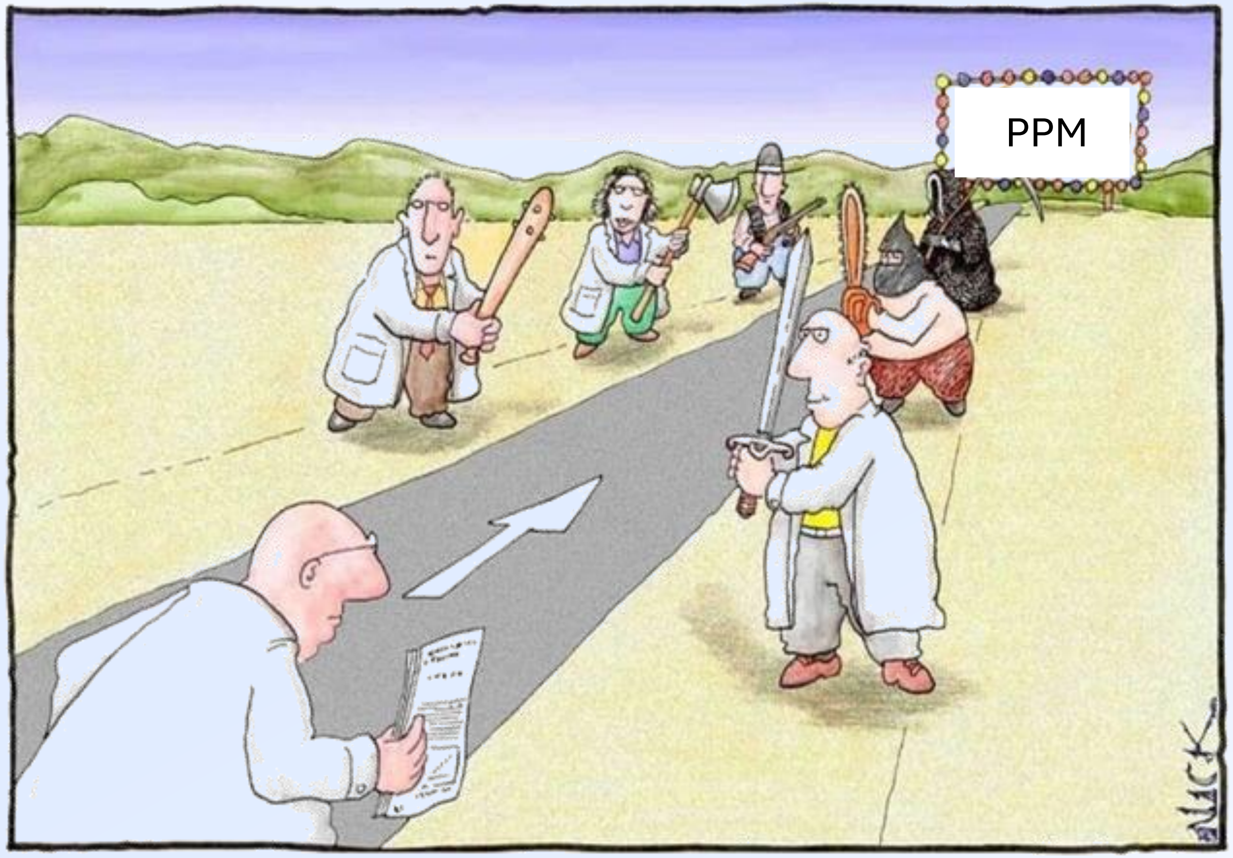
Pure QED theory of muonic atoms

- Fundamental constants (Rydberg, muon electron mass ratio, alpha, g-factors) are known well enough.
- Outside of the nucleus, QED seems to be well understood to sub ppm
- Various methods of calculation cross-checking each other (2603.25278)
- Some specific points of interest:

  SE-eVP, nuclear self energy, higher nuclear spins, recoil with realistic charge distributions, radiative-recoil …

The road to PPM accuracy:

- Resolving power
- Lineshape
- Calibration



- Electron screening
- Pure QED
- **Nuclear structure**

Nuclear Polarization seems to be manageable

- Nuclear pol is about 2 eV (10 ppm) for 2p in Z=20.
- Proportional to static dipole polarizability
- Sub ppm seems plausible for $Z \leq 20$

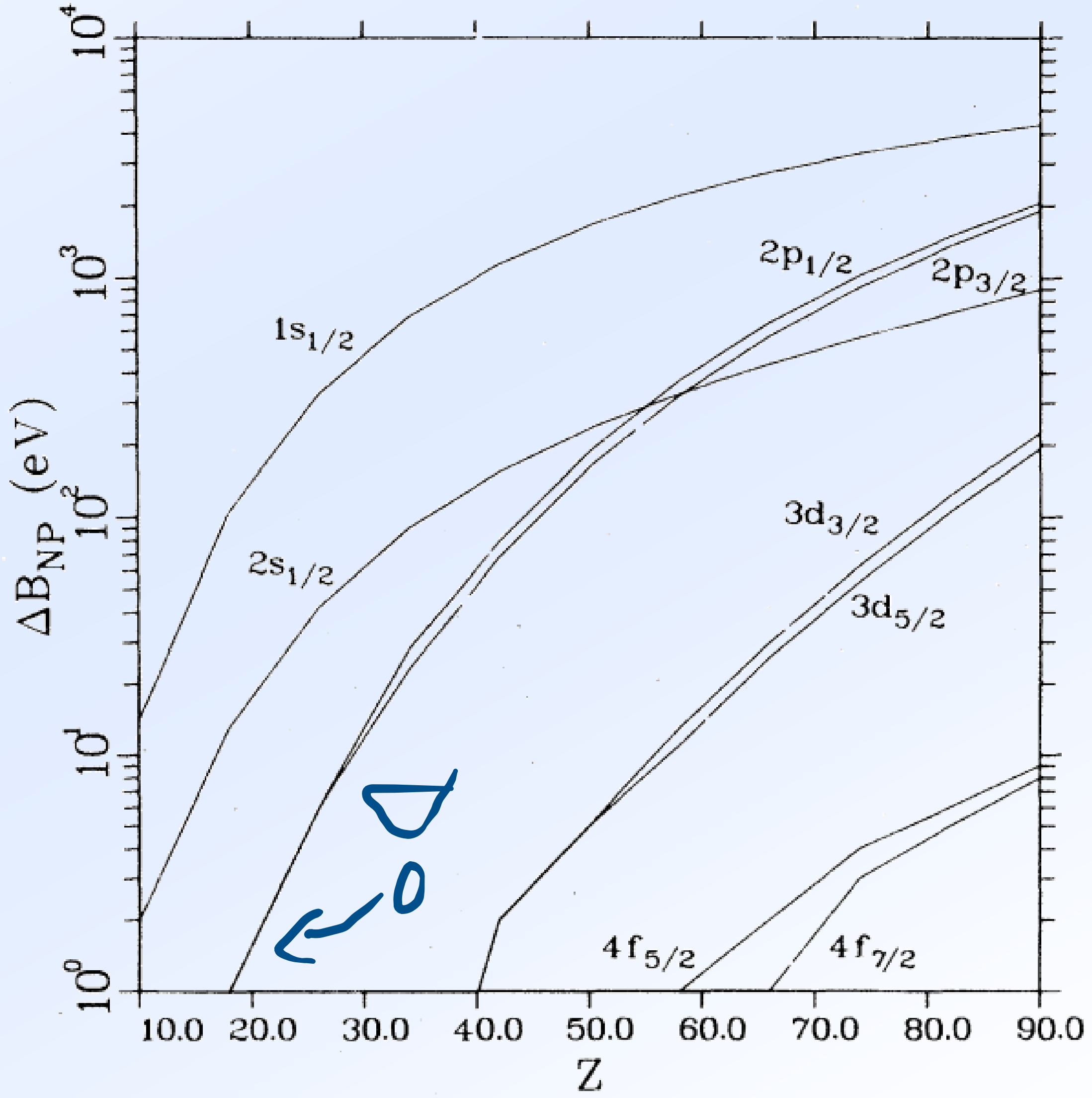


FIG. 4. Nuclear-polarization binding energy shifts (Rinker and Speth, 1978b).

QED theory of p-states (Patkos, Yerokhin, Pachucki, 022819):

Leading nuclear structure effects:

$$\mathcal{E}^{(6,0)}|_{J=1/2} = m_2 \left[\left(-\frac{5}{16\,n^6} + \frac{3}{4\,n^5} - \frac{3}{8\,n^4} - \frac{1}{8\,n^3} \right) + \frac{1}{6}\left(\frac{1}{n^3} - \frac{1}{n^5}\right) m_2^2\, r_c^2 + \frac{1}{45}\left(\frac{1}{n^3} - \frac{1}{n^5}\right) m_2^4\, r_{cc}^4 \right], \tag{78}$$

$$\mathcal{E}^{(6,0)}|_{J=3/2} = m_2 \left[\left(-\frac{5}{16\,n^6} + \frac{3}{8\,n^5} - \frac{3}{32\,n^4} - \frac{1}{64\,n^3} \right) + \frac{1}{45}\left(\frac{1}{n^3} - \frac{1}{n^5}\right) m_2^4\, r_{cc}^4 \right], \tag{80}$$

Plus eVP-FNS and SE-FNS that is proportional to r_c^2

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Need charge radius r_c, and 4th moment r_{cc}!

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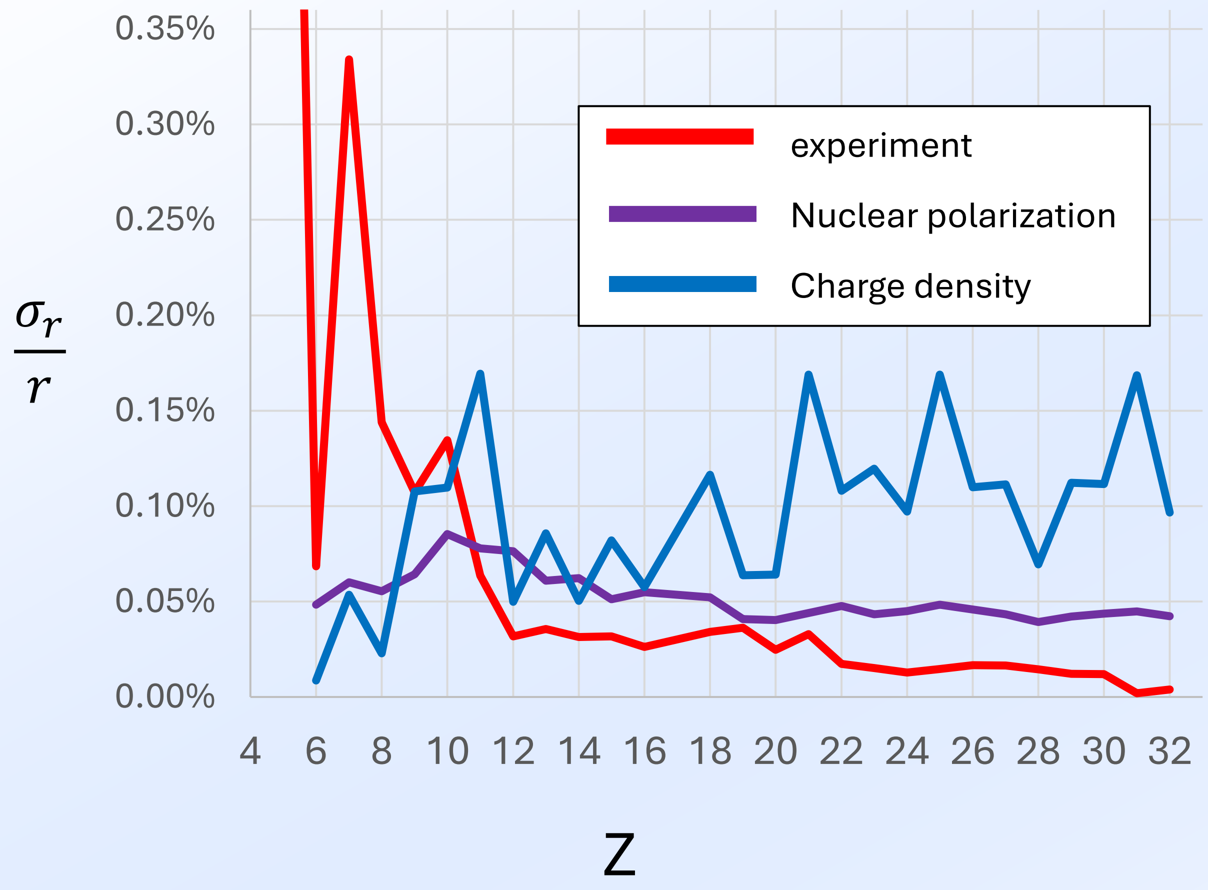
Need **charge radius** r_c, and 4th moment r_{cc}!

r_c mostly known to 10^{-3} + QUARTET for light nuclei

ADNDT



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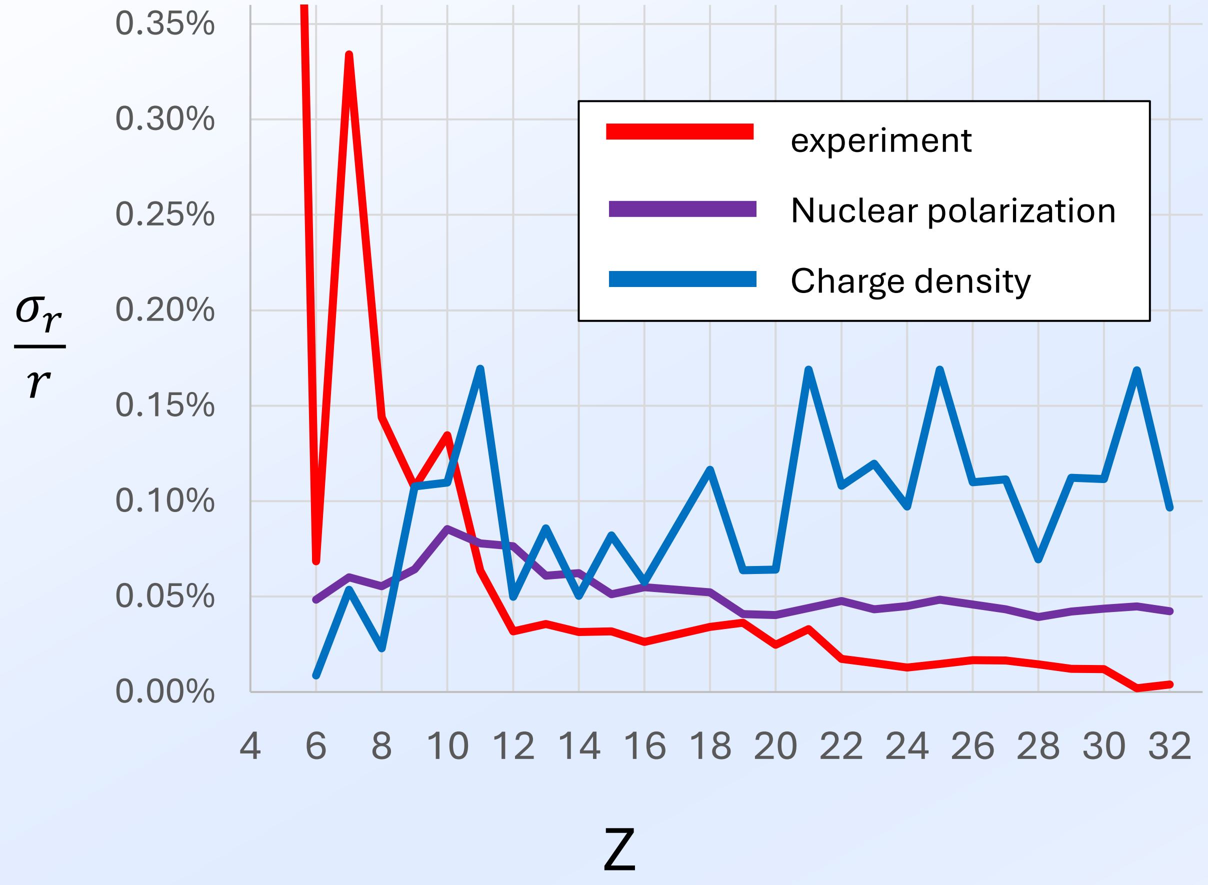

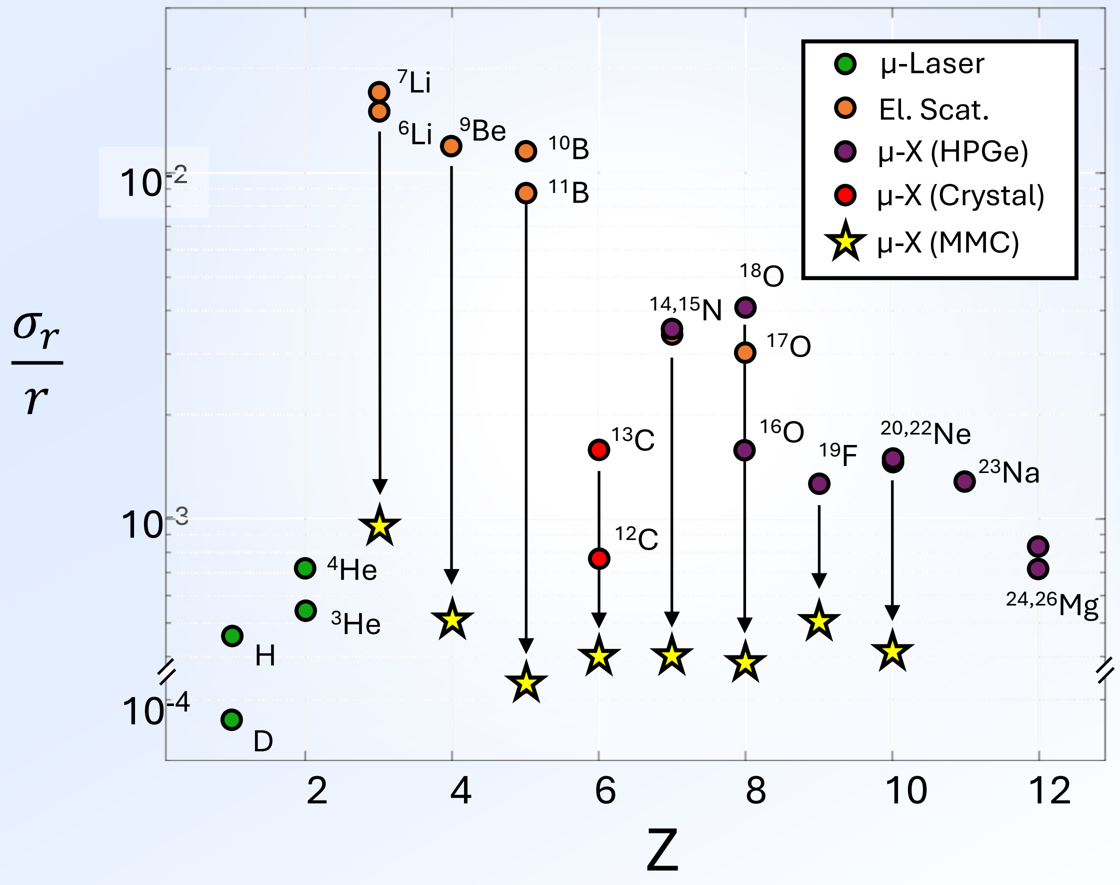

See Randolf's Talk on Wednesday

Working group on nuclear charge radii

Whitepaper available: arXiv:2604.08985

Welcoming your feedback

2025 Meeting of at IAEA headquarters

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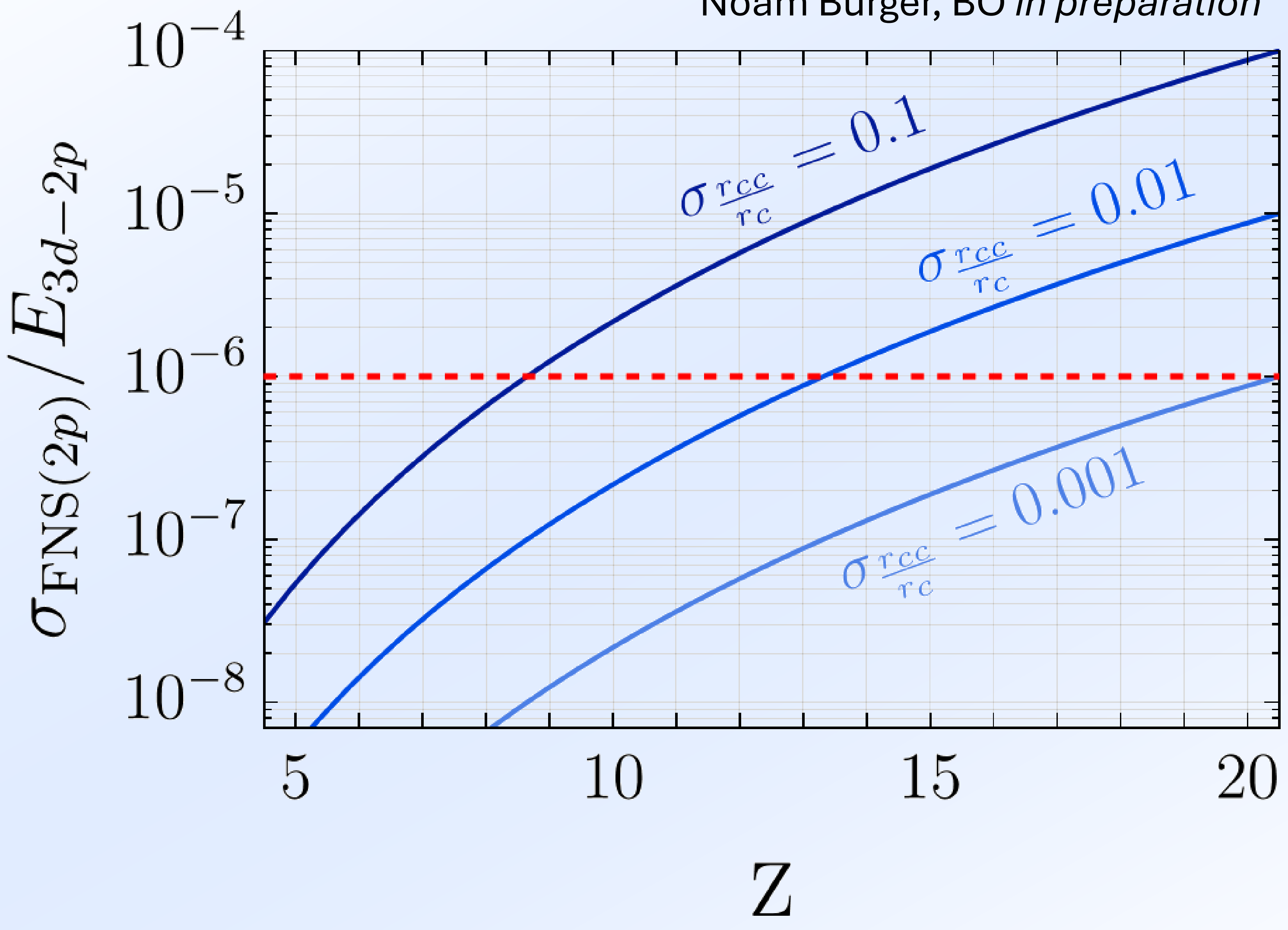
Need charge radius r_c, and **4th moment** r_{cc}!

Effect of uncertainty in 4th moment:

Noam Burger, BO *in preparation*



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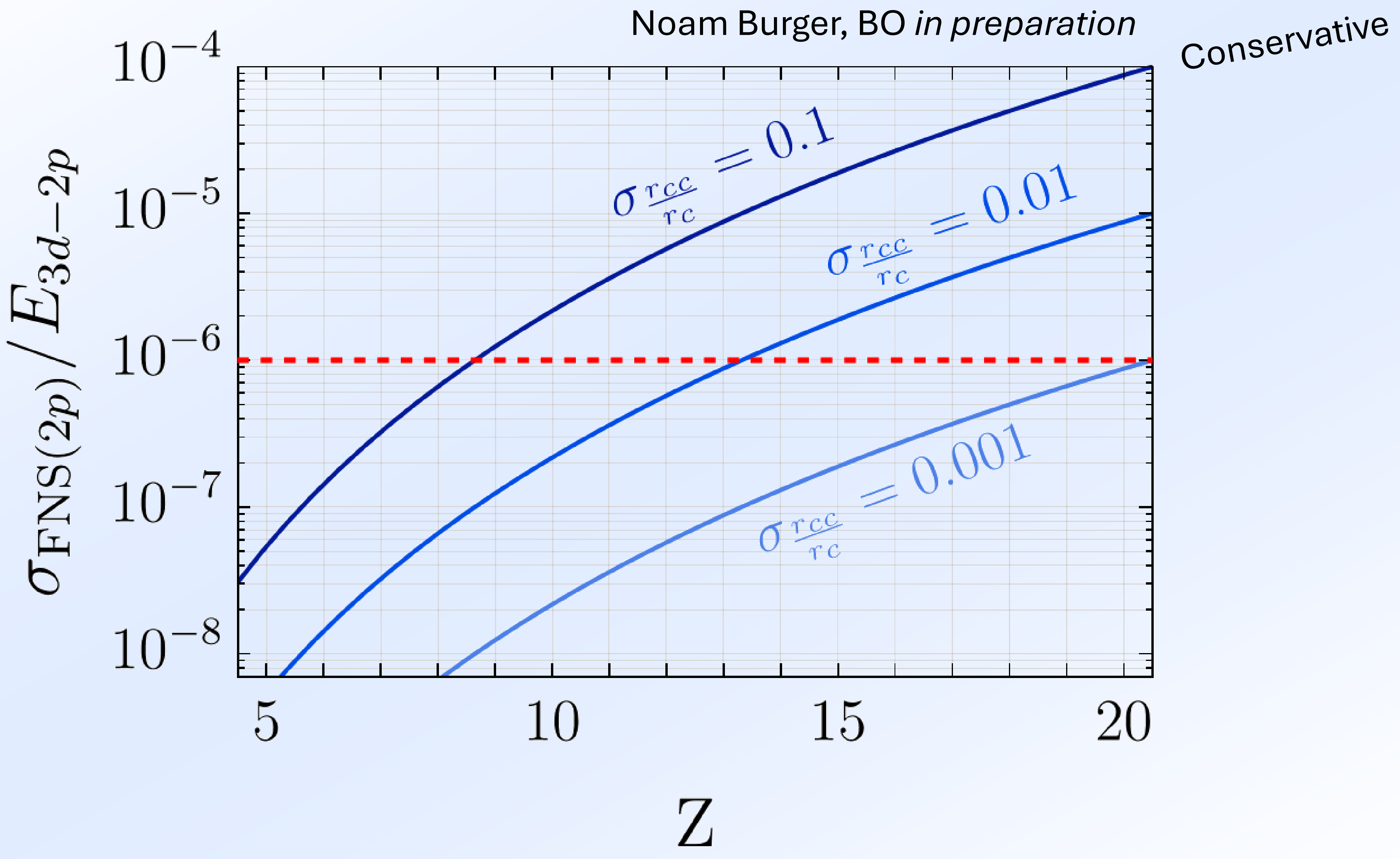

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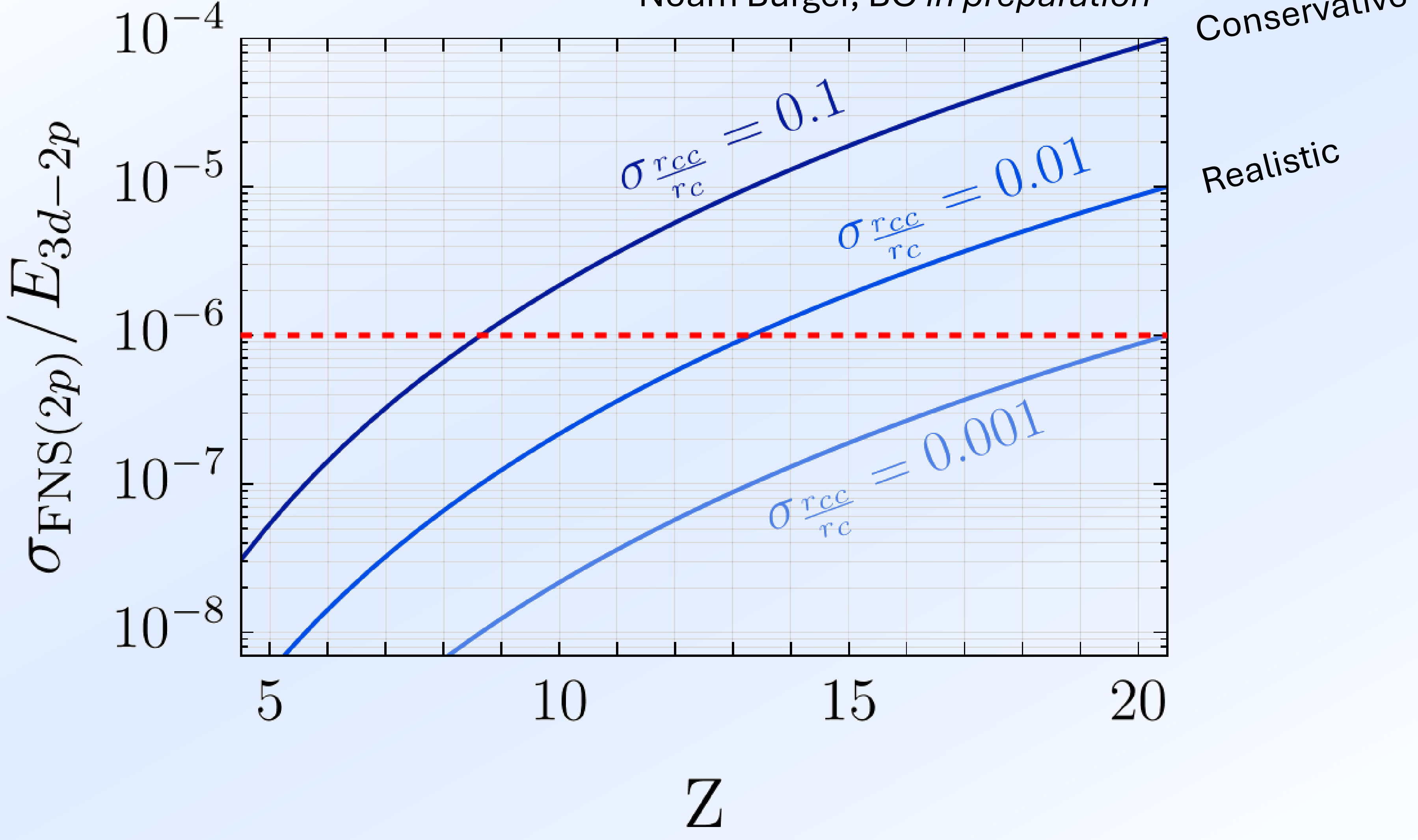

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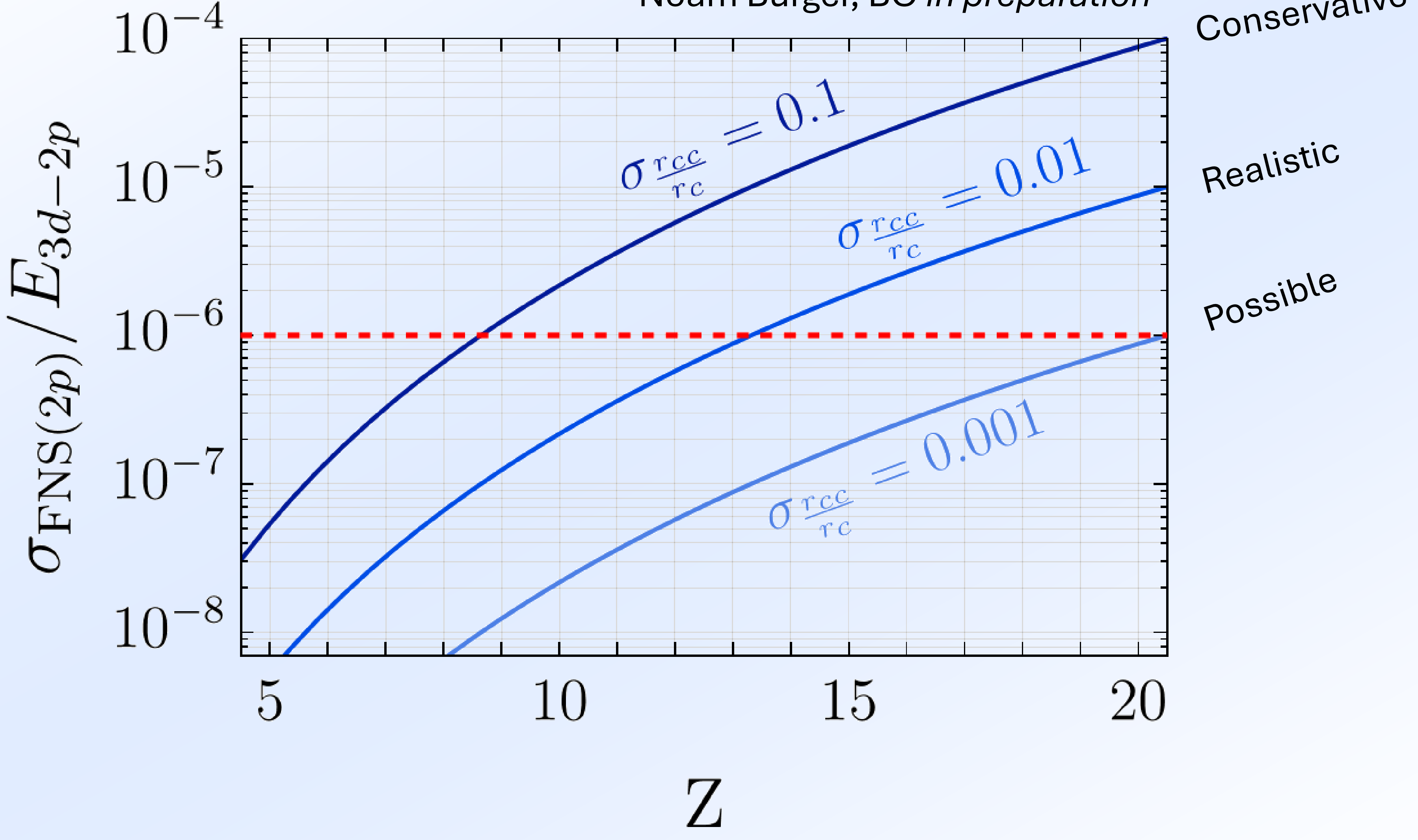

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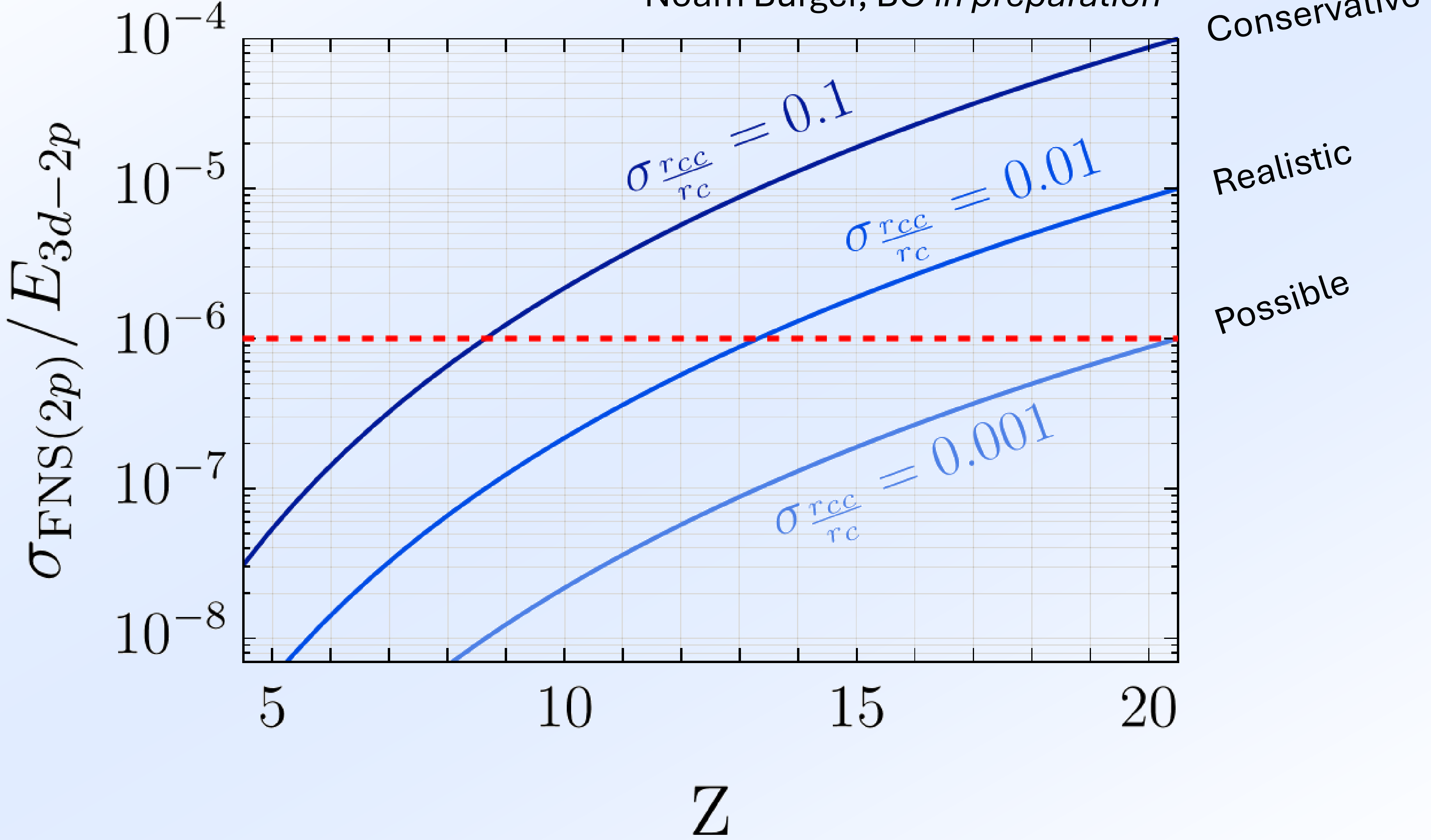
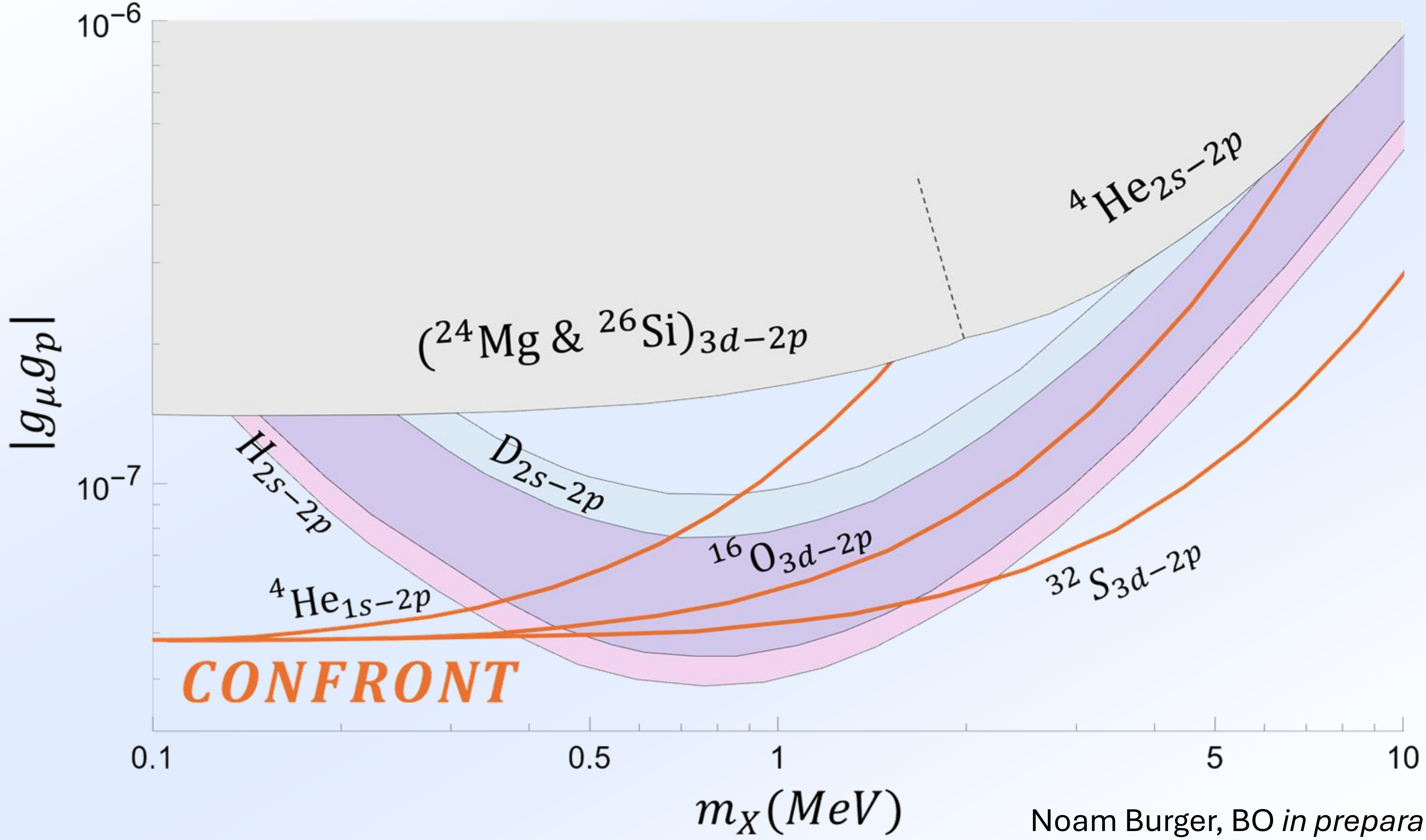


Prefer light or magic nuclei $Z \leq 20$

Prospects with PPM accuracy



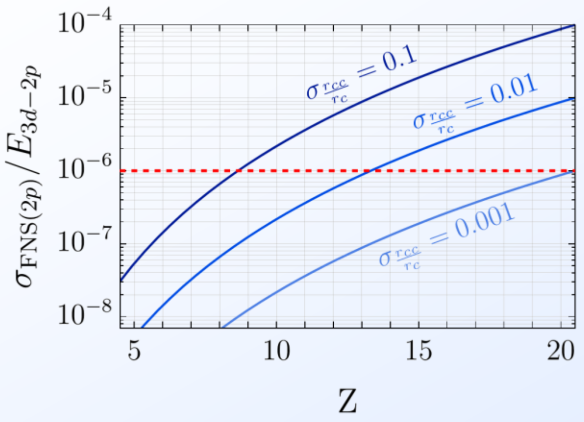
Noam Burger, BO *in preparation*

Are there 2 minutes left?

Rising importance of the 4th moment

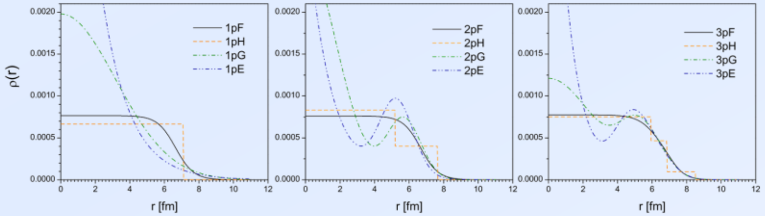
New physics searches in

contact-free transitions



Radii determinations in heavy

Muonic and Electronic Atoms

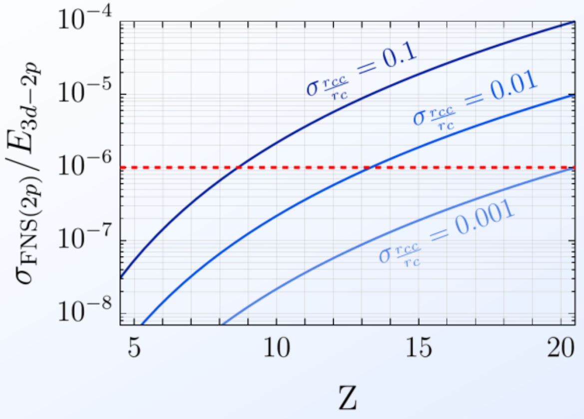


Natalia & Valdimir's talks

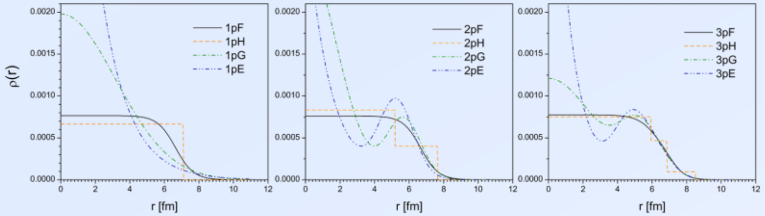
VA Yerokhin & BO PRA 113 (1), 012804

Rising importance of the 4th moment

New physics searches in contact-free transitions



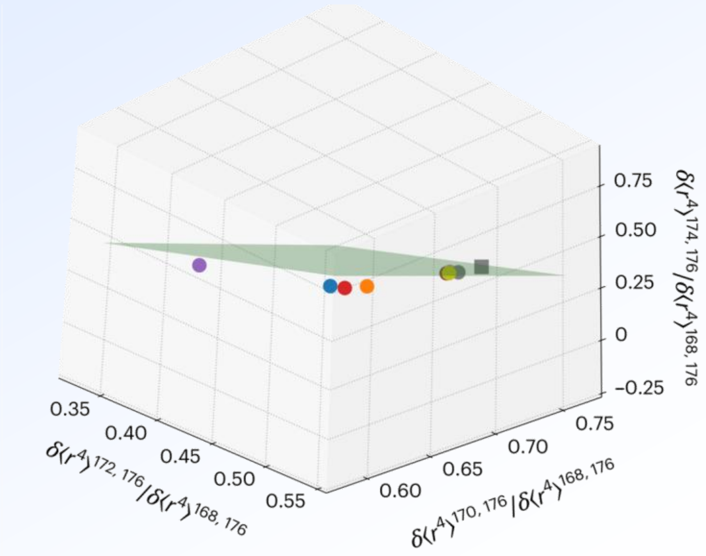
Radii determinations in heavy Muonic and Electronic Atoms



Natalia & Valdimir's talks

VA Yerokhin & BO PRA 113 (1), 012804

Taming KP nonlinearity:



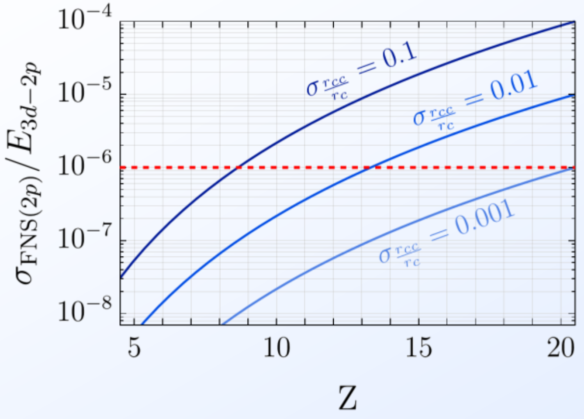
Constraints on nuclear factors by the dual King plot analysis.

Ishiyama et al. Nat. Phot. 20 504-511

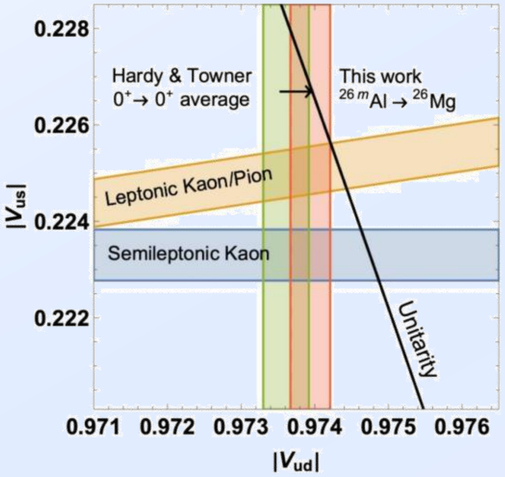
Rising importance of the 4th moment

New physics searches in

contact-free transitions



Taming nuclear size and **shape** effects in nuclear beta-decay



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Radii determinations in heavy

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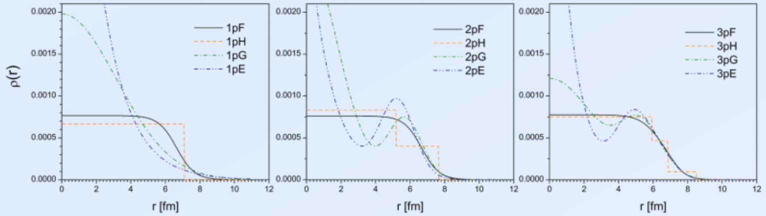

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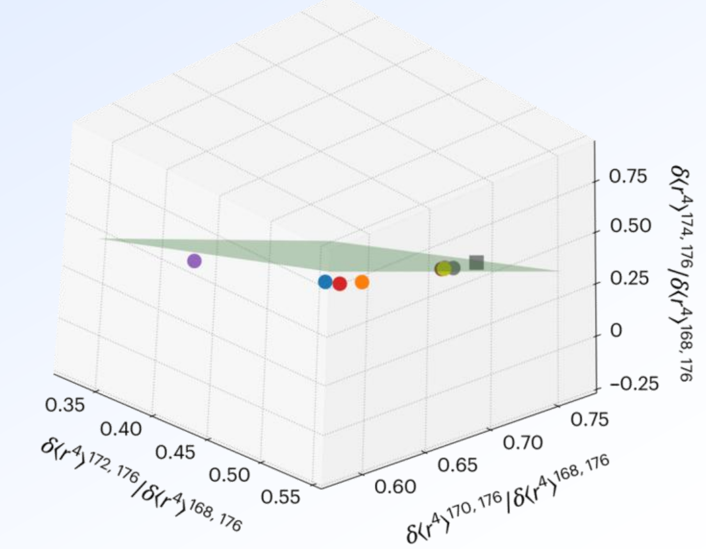

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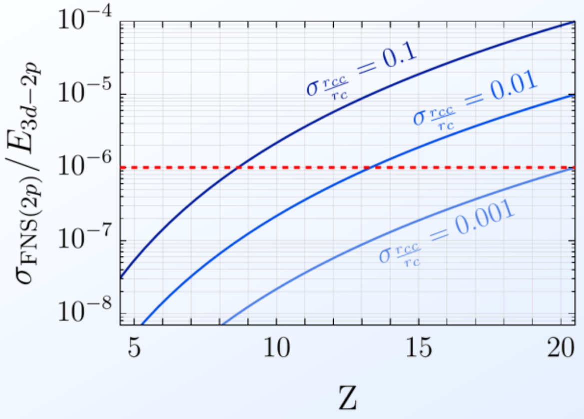

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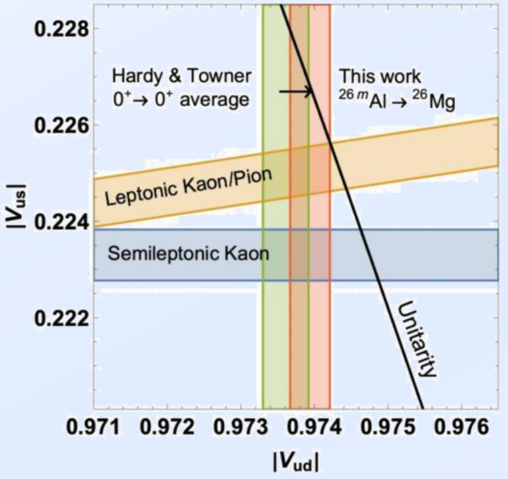

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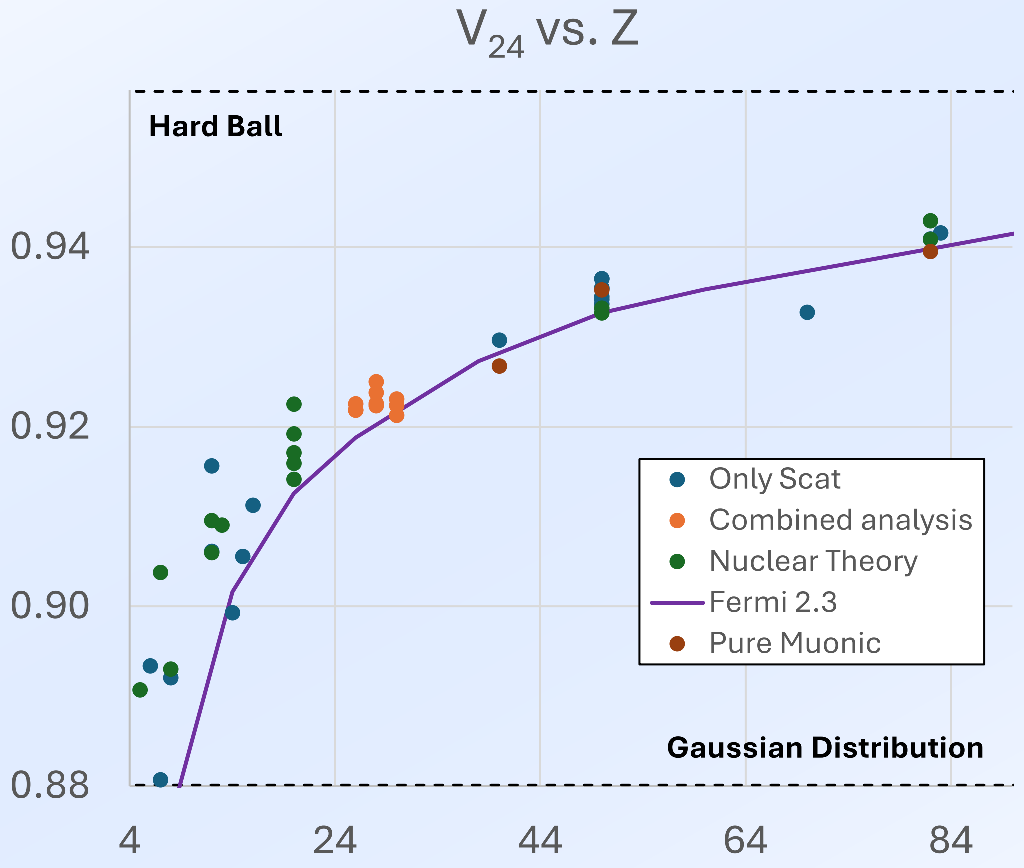
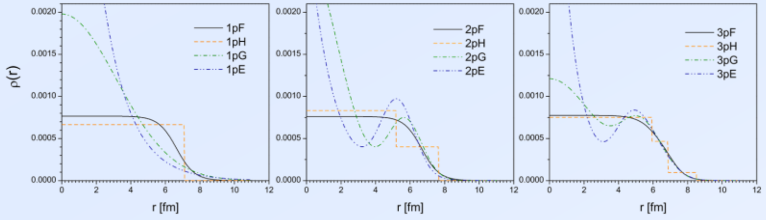
My new initiative:



Towards the first compilation of V_{24} factors

Radii determinations in heavy Muonic and Electronic Atoms



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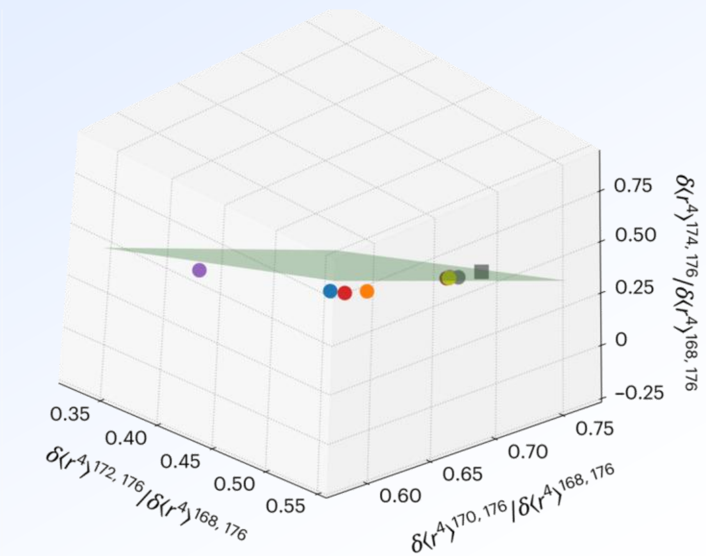

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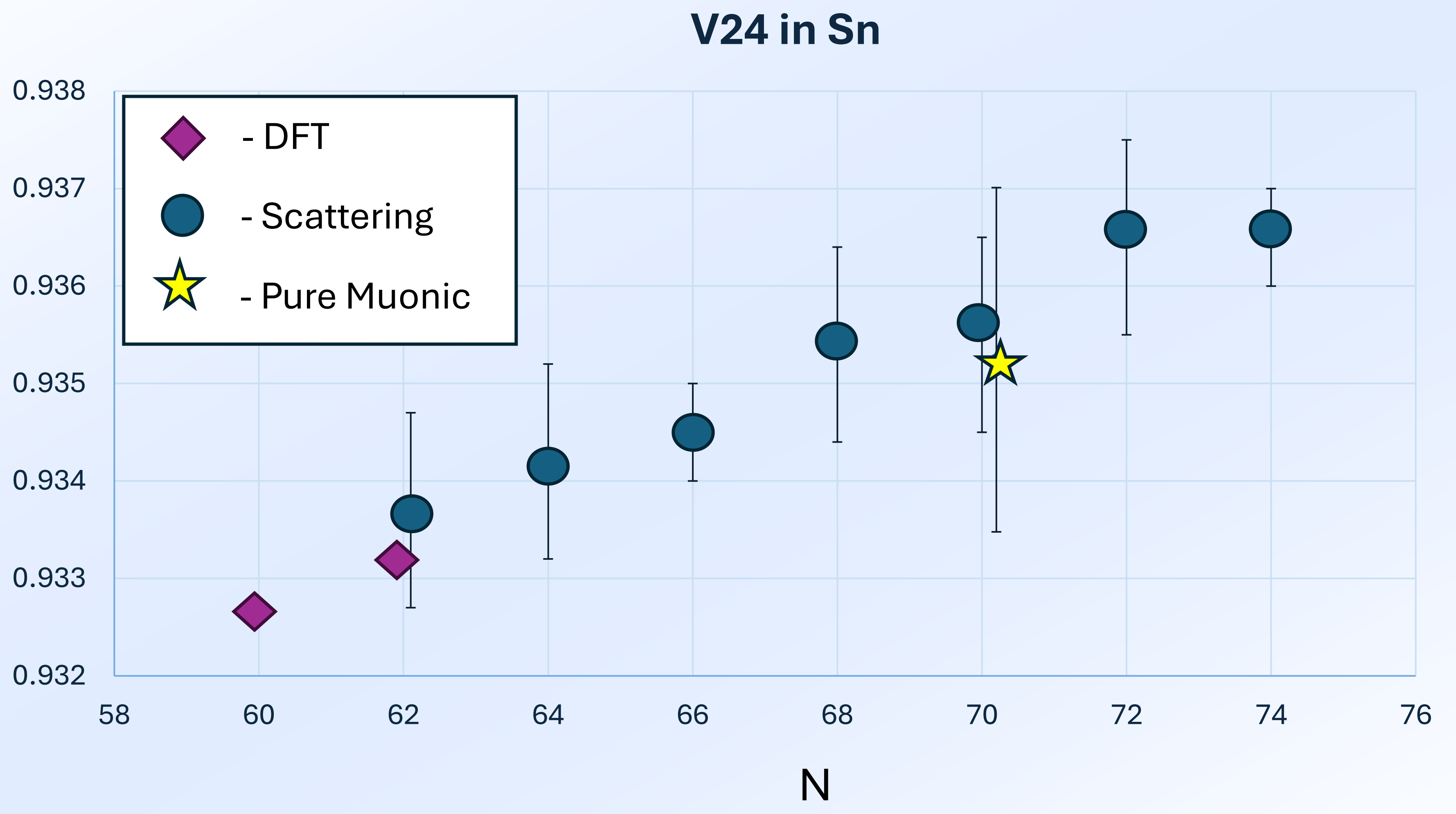
Preliminary: Isotopic variation in V factor



Simultaneous analysis of muonic atom energies is a superb way of determining v-factors with robust errorbars !
Need more measurements of **the other** transitions (not 2p-1s) !!!

See next talk !

Thanks for listening!

Exotic Atoms Lab @ Technion

Congratulations to Daniel Unger (KIP) !

QUARTET Beamtime 2025

bohayon@technion.ac.il

FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

WORKSHOP

FROM NUCLEAR STRUCTURE TO NEW PHYSICS

3 - 7 August 2026

ECT* - Villa Tambosi, Villazzano

ORGANIZERS

Mikhail **Gorshteyn -** JGU Mainz
Ayala **Glick-Magid -** University of Tel Aviv
Ben **Ohayon -** Technion IIT
Chien-Yeah **Seng -** University of Tennessee

MAIN TOPICS

- Beta decays and CKM unitarity
- Nuclear radii, structure and reactions
- Muonic and ordinary atoms
- Precision measurements
- Global electroweak fit
- SMEFT