Recent improvements in the theory of heavy muonic atoms and their influence on nuclear radii

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Outline

Historical introduction

Latest improvements

Preliminary results

Double checking

Additional problems

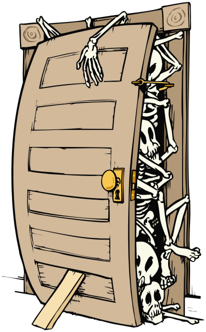
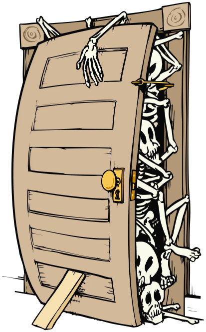


Fig: https://www.shackelfordfuneraldirectors.com/

Outline

- Historical introduction
- Latest improvements
- Preliminary results
- Double checking
- Additional problems



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How did it start: The Bible

Atomic Data and Nuclear Data Tables 99 (2013) 69–95

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Atomic Data and Nuclear Data Tables

journal homepage: www.elsevier.com/locate/adt

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Table of experimental nuclear ground state charge radii: An update

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A R T I C L E   I N F O

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Electron scattering
Muonic atom spectra

A B S T R A C T

The present table contains experimental root-mean-square (*rms*) nuclear charge radii R obtained by combined analysis of two types of experimental data: (i) radii changes determined from optical and, to a lesser extent, K_α X-ray isotope shifts and (ii) absolute radii measured by muonic spectra and electronic scattering experiments. The table combines the results of two working groups, using respectively two different methods of evaluation, published in ADNDT earlier. It presents an updated set of *rms* charge radii for 909 isotopes of 92 elements from $_{1}$H to $_{96}$Cm together, when available, with the radii changes from optical isotope shifts. Compared with the last published tables of R-values from 2004 (799 ground states), many new data are added due to progress recently achieved by laser spectroscopy up to early 2011. The radii changes in isotopic chains for He, Li, Be, Ne, Sc, Mn, Y, Nb, Bi have been first obtained in the last years and several isotopic sequences have been recently extended to regions far off stability, (e.g., Ar, Mo, Sn, Te, Pb, Po).

Shortly about muons and muonic atoms

Cute leptons source:
www.particlezoo.net

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- Same interaction laws, same formulas

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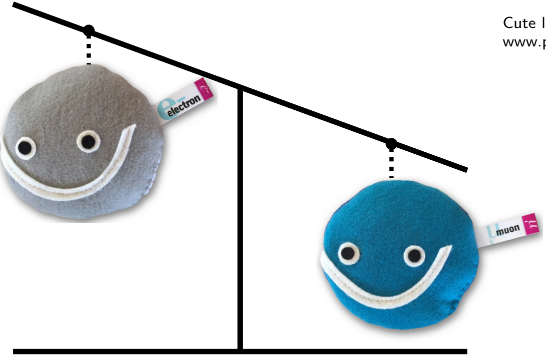

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- Heavy sibling of electron; $m_\mu \approx 207 m_e$

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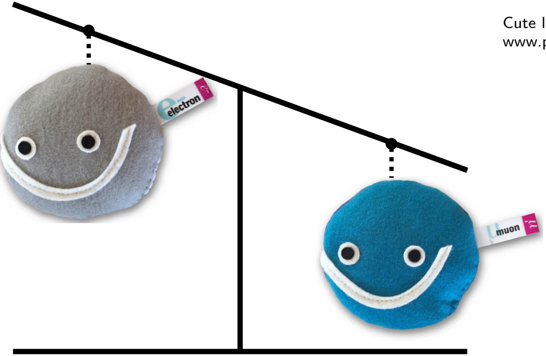

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- Lifetime 0.1-2.2 μs, capture and decay $10^{-12} - 10^{-9}$ s

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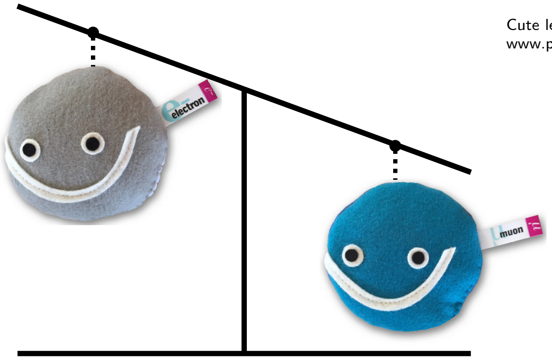

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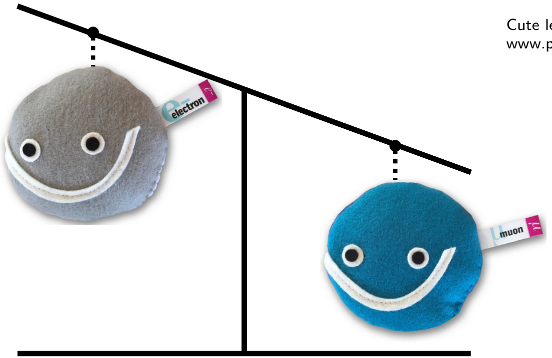

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far from
the nucleus

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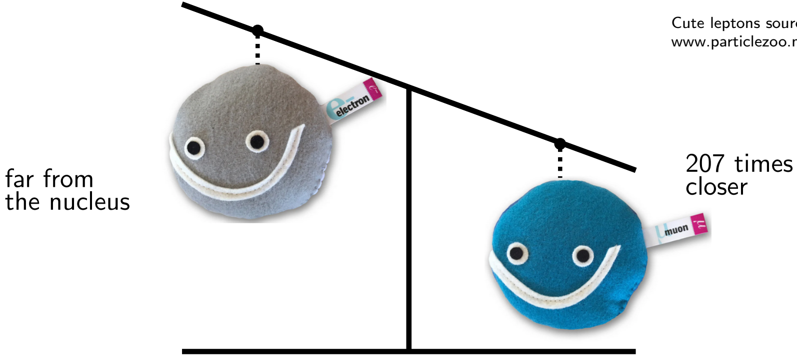

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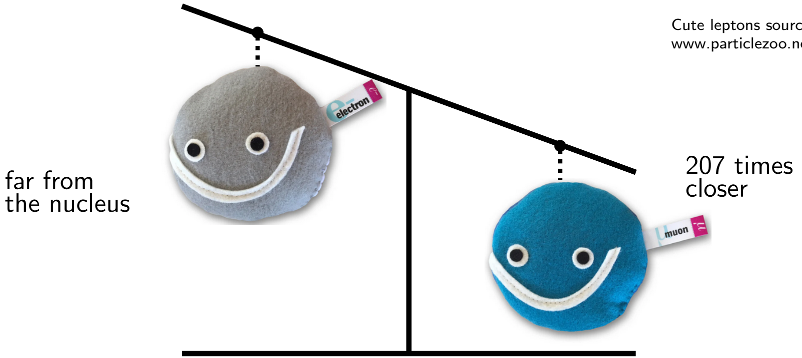

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- Same interaction laws, same formulas
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- Always hydrogen like, some electrons are far away
- Sensitive to nuclear structure

2016: restart of muonic physics

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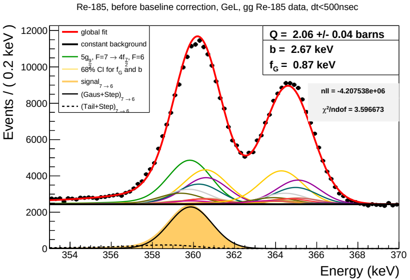
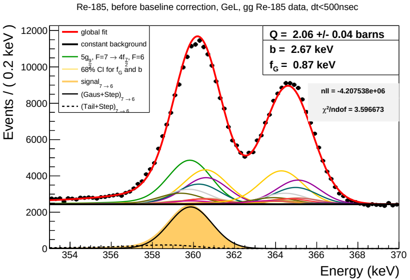
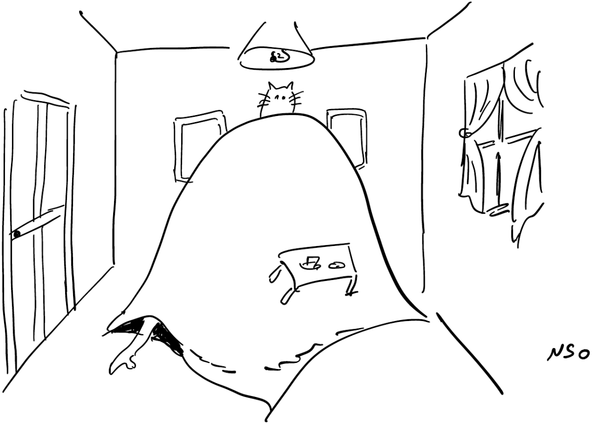


2016: restart of muonic physics



2022: Discovery of muonic fine-structure anomaly



[1] Yamazaki *et al.*, PRL **42**, 1470 (1979)
[2] Phan *et al.*, PRC **32**, 609 (1985)
[3] Bergem *et al.*, PRC **37**, 2821 (1988)
[4] Piller *et al.*, PRC **42**, 182 (1990)

What is the fine-structure anomaly

Very poor fit of experimental data for $2p_{3/2,1/2} \rightarrow 1s_{1/2}$ for muonic ^{90}Zr, $^{112-124}$Sn, ^{208}Pb

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$\to$ nuclear-polarization corrections as variable parameters

$$\Downarrow$$

the root of the problem

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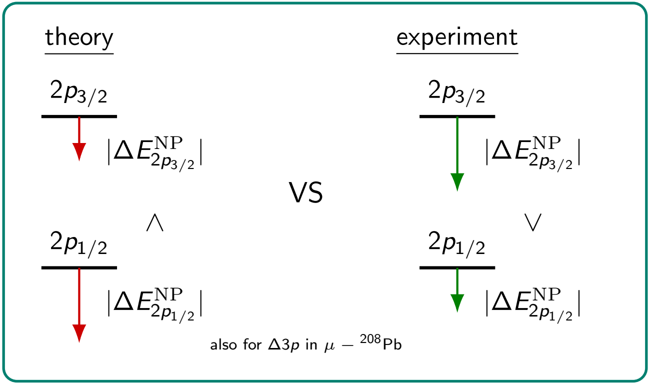
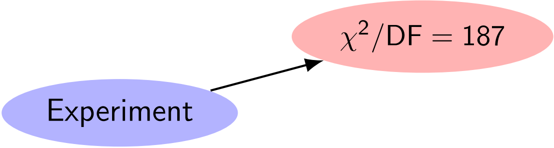


One of the best: ^{208}Pb

Experiment

[1] Bergem *et al.*, PRC **37**, 2821 (1988)

One of the best: ^{208}Pb



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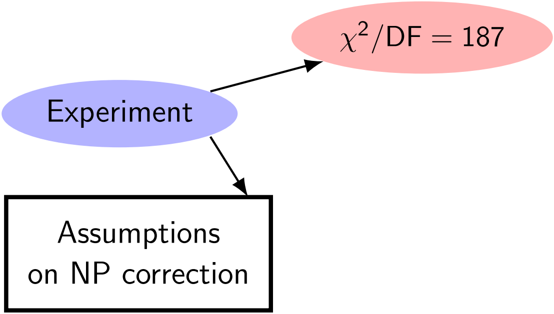

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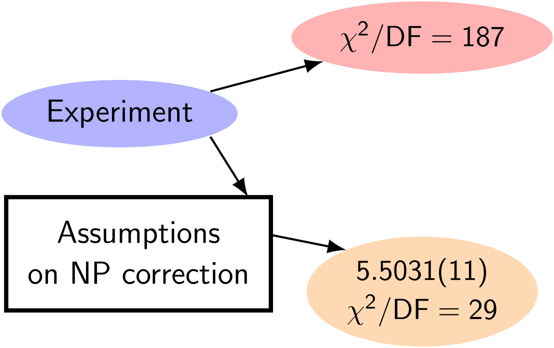

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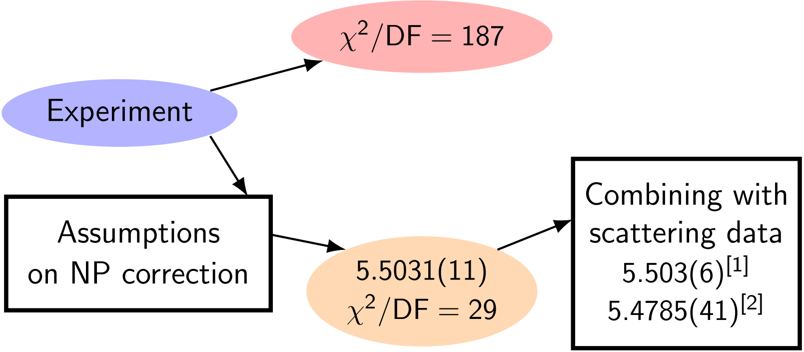

[1] Bergem *et al.*, PRC **37**, 2821 (1988)
[2] Fricke and Bernhardt, At. Data Nucl. Data Tables **60**, 177 (1995)

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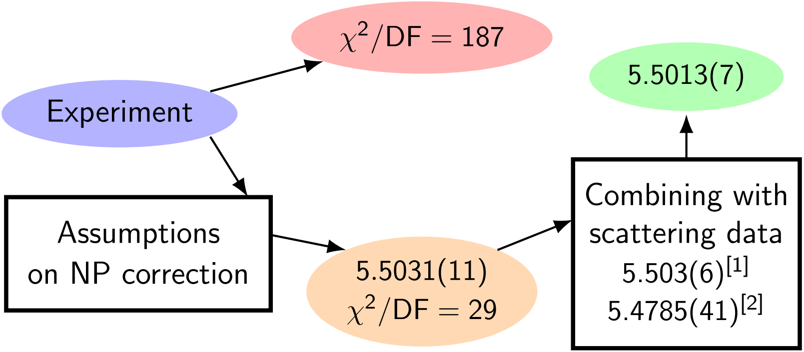

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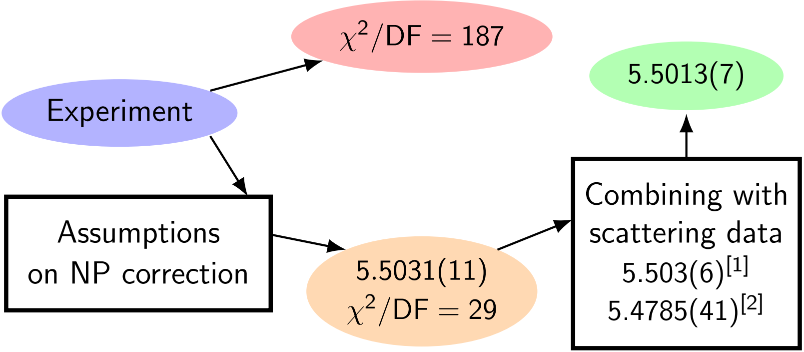
One of the best: ^{208}Pb rms=5.5012(13)



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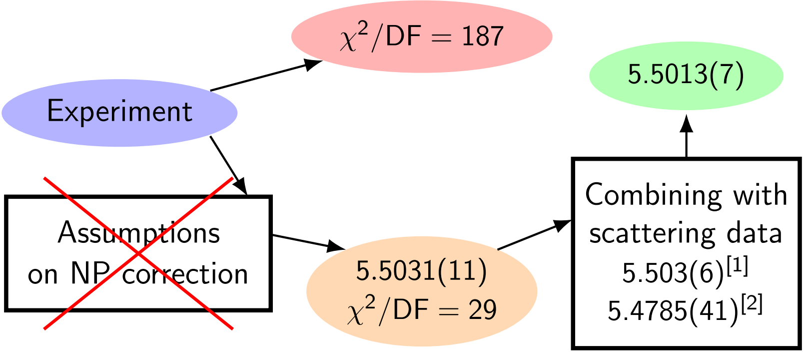

[1] Bergem *et al.*, PRC **37**, 2821 (1988)
[2] Fricke and Bernhardt, At. Data Nucl. Data Tables **60**, 177 (1995)
[3] Valuev *et al.*, PRL **128** 203001 (2022)

Nuclear polarization effect

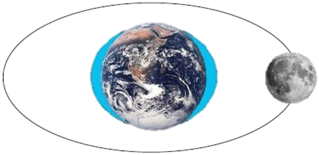

Image source: www.universetoday.com

$$V_{\mathrm{Coul}}(r) = -\frac{\alpha Z}{r}$$

$$V_{\mathrm{ext}}(r) = -\alpha \int \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}'$$

$$V_{\mathrm{NP}}(r) = -\alpha \sum_{Z} \frac{1}{|\mathbf{r}-\mathbf{r}_{\mathbf{N_i}}|}$$

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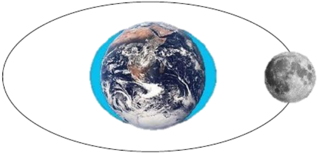

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$$H = H_N + \boldsymbol{\alpha}\mathbf{p} + \beta m_\mu + V(\mathbf{r}, \mathbf{r}_{N_i})$$

$$\Delta E_l = {\sum_{nN}}' \frac{\langle aA|\Delta V|nN\rangle\langle nN|\Delta V|aA\rangle}{E_{aA}-E_{nN}}$$

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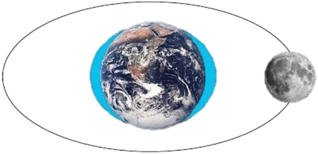

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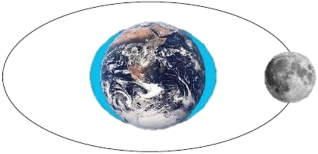
$$\langle aA|\Delta V|nN\rangle = \langle aA| \sum_{Z} \sum_{lm} \frac{\min(r, r_{N_i})^l}{\max(r, r_{N_i})^{l+1}} Y_{lm} Y^*_{lm} |nN\rangle$$

Nuclear polarization effect



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Light muonic atoms: $|a\rangle \to \delta(0)$

Heavy highly charge ions: $|A\rangle \to \delta(R)$

Transverse part of muon-nucleus interaction

$$H = H_N + \boldsymbol{\alpha}\mathbf{p} + \beta m_\mu + V(\mathbf{r}, \mathbf{r}_{N_i})$$

$$\Downarrow$$

$$H = H_N + \boldsymbol{\alpha}(\mathbf{p} - e\mathbf{A}(\mathbf{r}, \mathbf{r}_{N_i})) + \beta m_\mu + V(\mathbf{r}, \mathbf{r}_{N_i})$$

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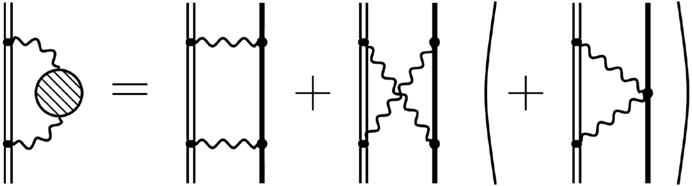
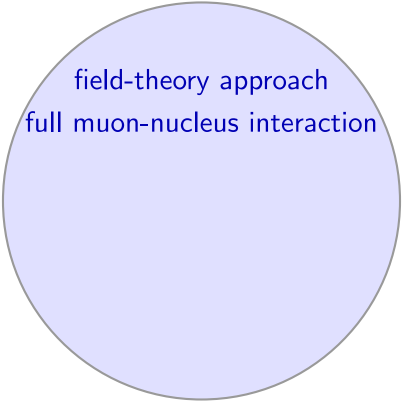


$$\Delta E^{\mathrm{L}}_{\mathrm{NP}} = -i(4\pi\alpha)^2 \sum_{i'I'} \iint \frac{d\boldsymbol{q}\, d\boldsymbol{q}'}{(2\pi)^6} \int \frac{d\omega}{2\pi} \frac{D_{\mu\xi}(\omega, \boldsymbol{q}) D_{\zeta\nu}(\omega, \boldsymbol{q}') \langle iI | j^\mu_m(-\boldsymbol{q}) J^\xi_N(\boldsymbol{q}) | i'I' \rangle \, \langle i'I' | J^\zeta_N(-\boldsymbol{q}') j^\nu_m(\boldsymbol{q}') | iI \rangle}{(\omega + \omega_m - iE_{i'}\epsilon)(\omega - \omega_N + i\epsilon)},$$

$$\Delta E^{\mathrm{X}}_{\mathrm{NP}} = +i(4\pi\alpha)^2 \sum_{i'I'} \iint \frac{d\boldsymbol{q}\, d\boldsymbol{q}'}{(2\pi)^6} \int \frac{d\omega}{2\pi} \frac{D_{\mu\xi}(\omega, \boldsymbol{q}) D_{\zeta\nu}(\omega, \boldsymbol{q}') \langle iI' | j^\mu_m(-\boldsymbol{q}) J^\xi_N(\boldsymbol{q}) | i'I \rangle \, \langle i'I | J^\zeta_N(-\boldsymbol{q}') j^\nu_m(\boldsymbol{q}') | iI' \rangle}{(\omega + \omega_m - iE_{i'}\epsilon)(\omega + \omega_N - i\epsilon)},$$

$$\Delta E^{\mathrm{SG}}_{\mathrm{NP}} = -i(4\pi\alpha)^2 \sum_{i'} \iint \frac{d\boldsymbol{q}\, d\boldsymbol{q}'}{(2\pi)^6} \int \frac{d\omega}{2\pi} \frac{D_{\mu\xi}(\omega, \boldsymbol{q}) \delta^{\xi\zeta} D_{\zeta\nu}(\omega, \boldsymbol{q}') \langle i | j^\mu_m(-\boldsymbol{q}) | i' \rangle \, \langle i' | j^\nu_m(\boldsymbol{q}') | i \rangle}{(\omega + \omega_m - iE_{i'}\epsilon)} \frac{\langle I | \rho_N(\boldsymbol{q} - \boldsymbol{q}') | I \rangle}{m_p}.$$

Our goal



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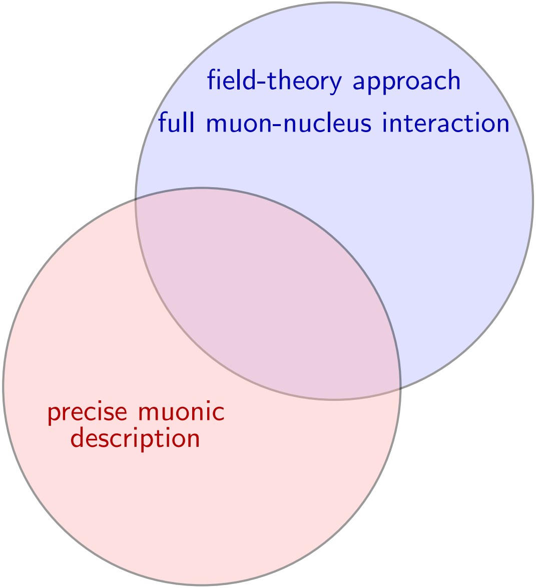
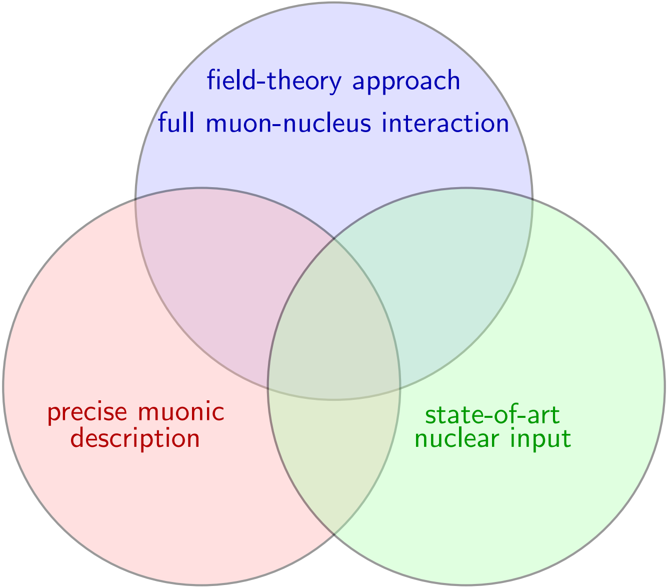

field-theory approach
full muon-nucleus interaction
precise muonic
description

Our goal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state-of-art nuclear input

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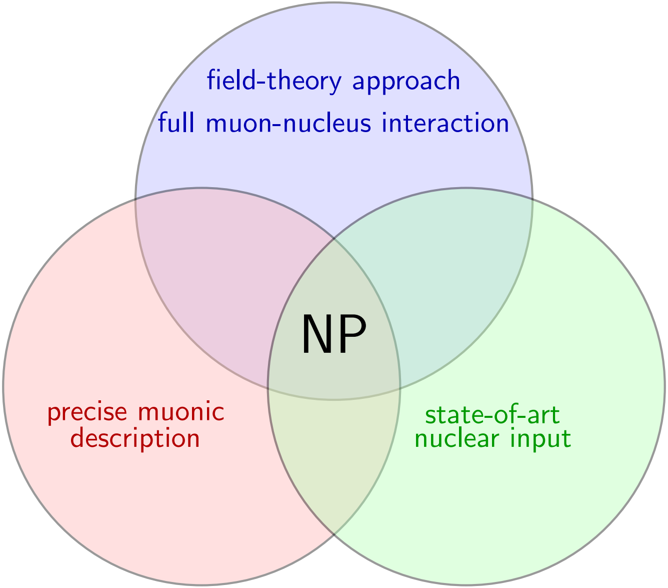
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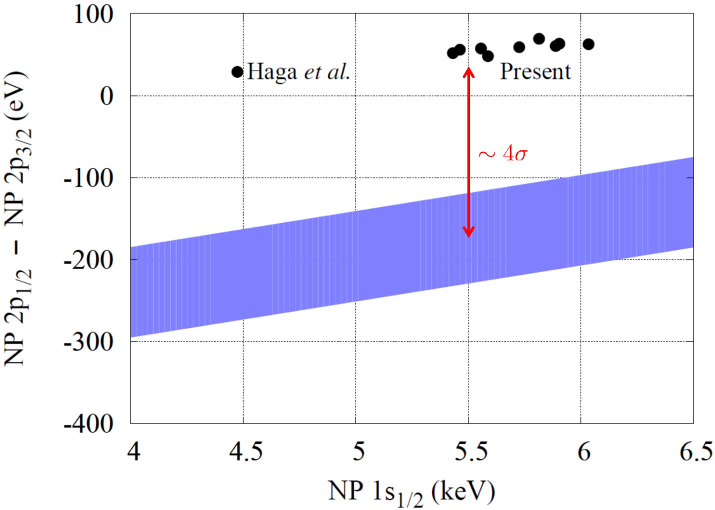
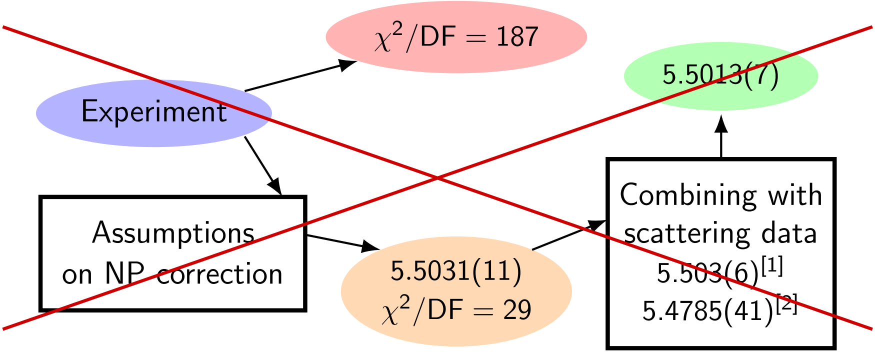
Nuclear polarization correction ^{208}Pb



around 150 eV, or 4σ standard deviations gap

Valuev *et al.*, PRL **128** 203001 (2022)

One of the best: ^{208}Pb rms=5.5012(13)?



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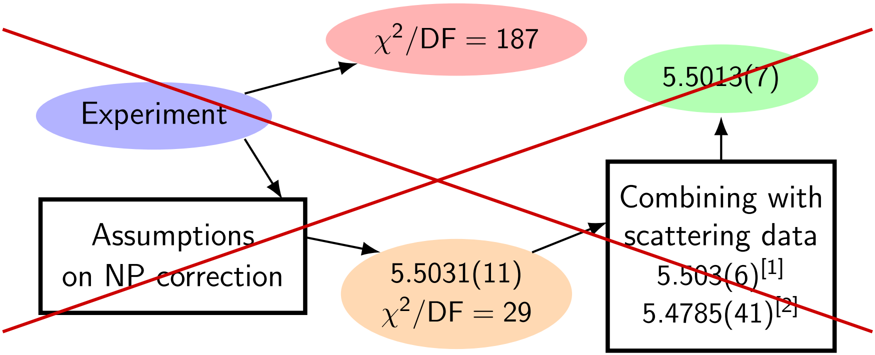
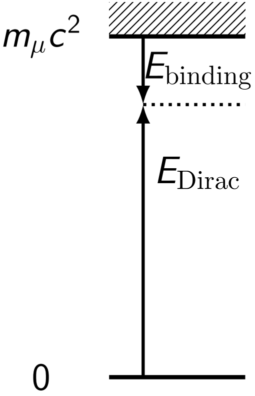


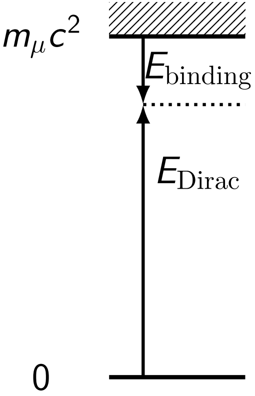
Total reevaluation of all QED and nuclear effects is needed

Dirac value and nuclear size



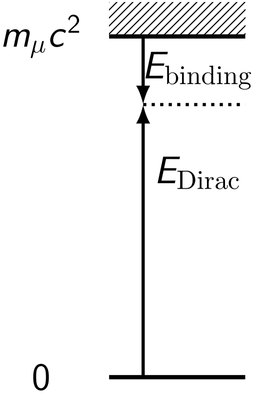
- Muons are close to the nucleus, relativistic $\rightarrow$ Dirac equation

Dirac value and nuclear size



- Muons are close to the nucleus, relativistic → Dirac equation
- $m_\mu c^2 \approx 100$ MeV
  $E_\mathrm{Dirac} \approx 80$ MeV
  $E_\mathrm{binding} \approx 20$ MeV

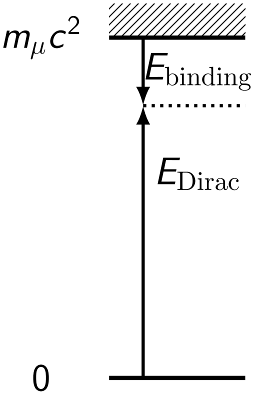
Dirac value and nuclear size



- Muons are close to the nucleus, relativistic $\rightarrow$ Dirac equation
- $m_\mu c^2 \approx 100$ MeV
  $E_{\rm Dirac} \approx 80$ MeV
  $E_{\rm binding} \approx 20$ MeV
- Extended nucleus: sphere,

$$V_{\rm Sph}(r) = \begin{cases} a + br^2; & r \leq R \\ -\frac{Z\alpha}{r}; & r \geq R \end{cases}$$

Dirac value and nuclear size



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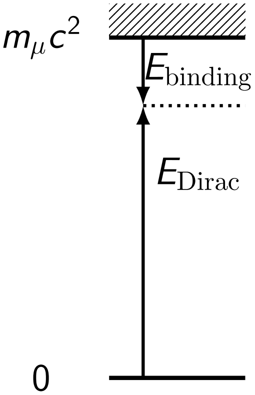
  $E_{\mathrm{Dirac}} \approx 80$ MeV
  $E_{\mathrm{binding}} \approx 20$ MeV

- Extended nucleus: sphere, Fermi,

$$\rho^F_{a,c}(r_\mu) = \frac{N}{1 + \mathrm{e}^{(r-c)/a}}$$

Dirac value and nuclear size



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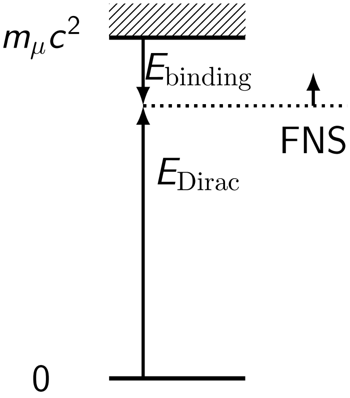
  $E_{\mathrm{binding}} \approx 20$ MeV
- Extended nucleus: sphere, Fermi, deformed Fermi

$$\rho_{a,c,\beta}(r_\mu, \vartheta_\mu) = \frac{N}{1 + e^{[r - c(1+\beta Y_{20}(\vartheta_\mu))]/a}}$$

Dirac value and nuclear size



- Muons are close to the nucleus, relativistic → Dirac equation

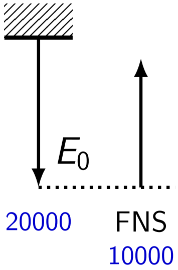
- $m_\mu c^2 \approx 100$ MeV
  $E_{\mathrm{Dirac}} \approx 80$ MeV
  $E_{\mathrm{binding}} \approx 20$ MeV

- Extended nucleus: sphere, Fermi, deformed Fermi

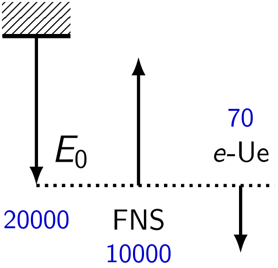
$$\rho_{a,c,\beta}(r_\mu, \vartheta_\mu) = \frac{N}{1 + e^{[r - c(1+\beta Y_{20}(\vartheta_\mu))]/a}}$$

- $\Delta E_{\mathrm{FNS}} \approx 10$ MeV

QED effects:



QED effects: Uehling

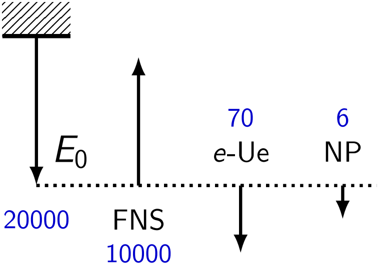


$$V_{\mathrm{Ue}}(r) = -\frac{2\alpha Z\alpha}{3r}\int_0^\infty dr' r' \rho(r')\left[\chi_2(2|r-r'|) - \chi_2(2|r+r'|)\right]$$

$$V_{\mathrm{Ue}}(r) = V_{\mathrm{point}}(r)\left[\frac{2\alpha}{3\pi}\chi_1(2r)\right]$$

$$V_{\mathrm{Ue}}(r) \approx V_{\mathrm{Fermi}}(r)\left[\frac{2\alpha}{3\pi}\chi_1(2r)\right]$$

QED effects: Nuclear polarization



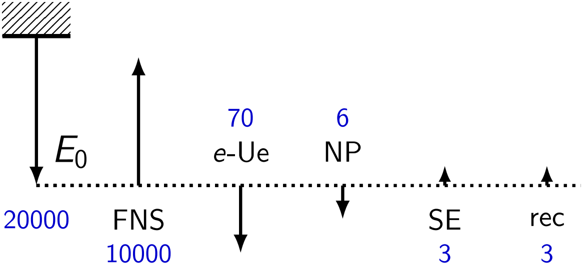
Improvements:

- field-theory approach, including transverse part
- state-of-art muonic and nuclear input, model dependence
- $0^+, 1^-, 2^+, 3^-, 4^+, 5^-$ and 1^+ excitation modes

- 4252 eV $\rightarrow$ 5712 eV

Valuev *et al.*, PRL **128** 203001 (2022)

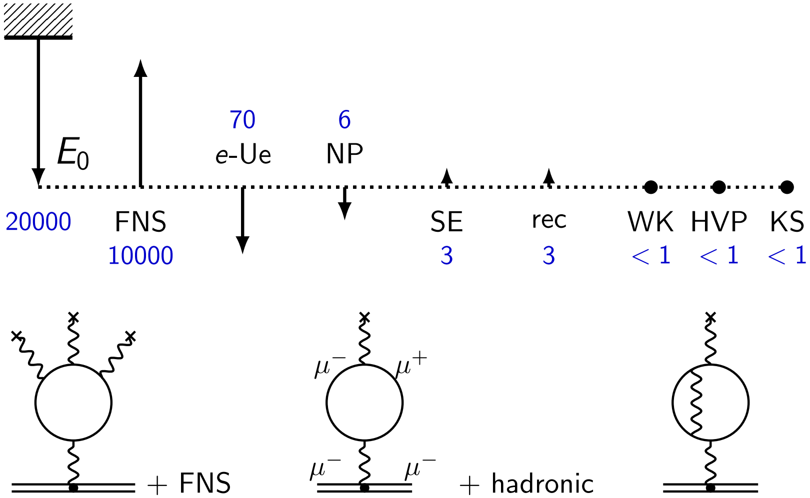
QED effects: Self energy and recoil



- rigorous QED calculations
- ΔE_{SE} =3270(160)[1], 3373[2] eV $\rightarrow$ 3225(15)[3] eV
- ΔE_{rec} =385[4]* eV $\rightarrow$ 3902[5] eV

[1] Cheng *et al.*, PRA **17**, 489 (1978)
[2] Haga *et al.*, PRC **75**, 044315 (2007)
[3] Oreshkina, PRR **4**, L042040 (2022)
[4] Bergem *et al.*, PRC **37**, 2821 (1988)
[5] Yerokhin and Oreshkina, PRA **108**, 052824 (2023)

QED effects: sub-leading



in preparation

Results for ^{208}Pb RMS extraction PRELIMINARY

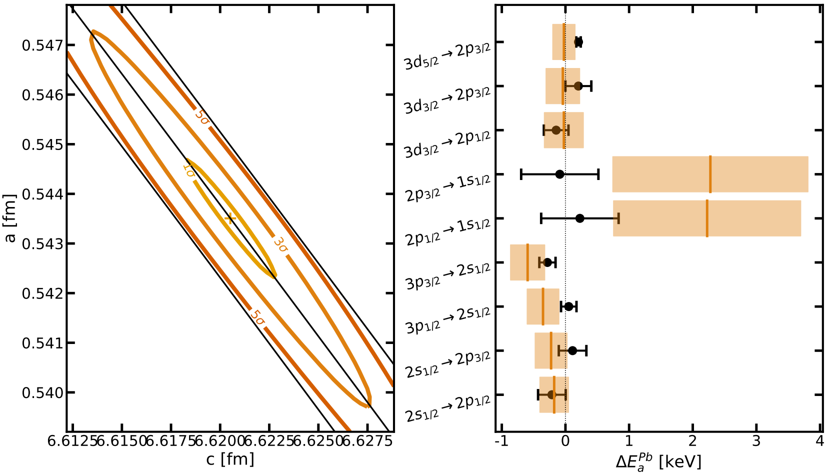
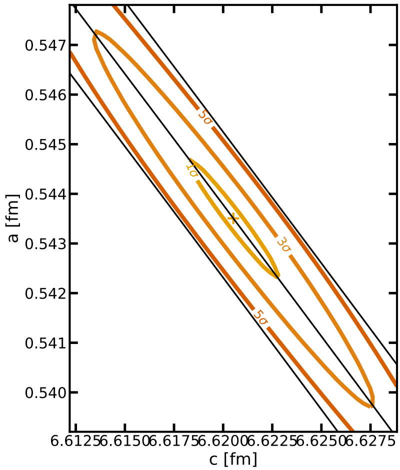
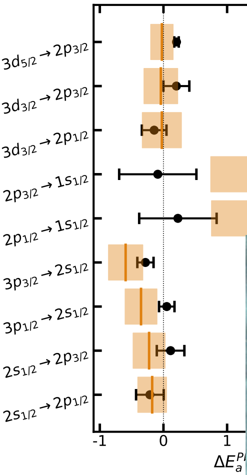


Fig: Konstantin Beyer

Results for ^{208}Pb RMS extraction PRELIMINARY





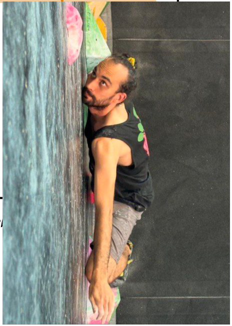
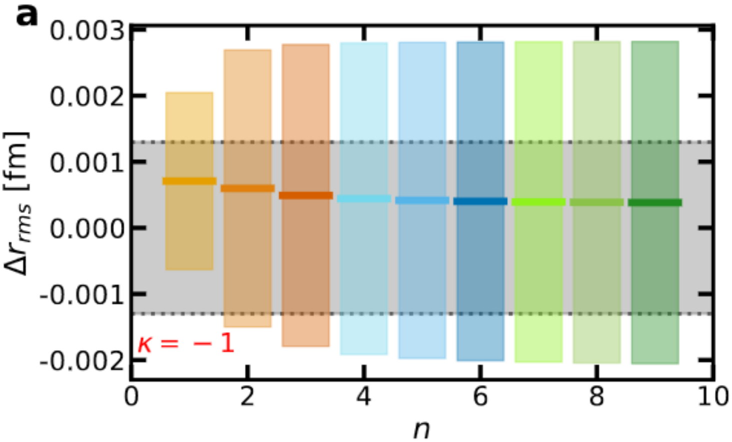


Fig: Konstantin Beyer

Model dependence PRELIMINARY



The difference between the Fermi-equivalent radius and the tabulated value. The solid colourful line is the mean value over all SKYRME distributions.

Fig: Konstantin Beyer

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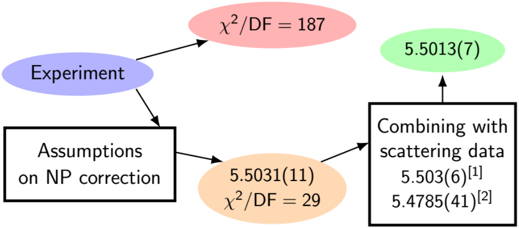

Theory uncertainties

- Completely ignored in previous studies

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- Adding uncertainties (improving the results) will lead to visibly worse outcome

Barrett radii

$$E_{if}^{\mathrm{FNS}} \approx C \int d^3 r \rho_c(\mathbf{r}) r^k e^{-\alpha_B r} \equiv B_{if}(C, k, \alpha_B)$$

α_B is commonly fixed to be the same for all transitions

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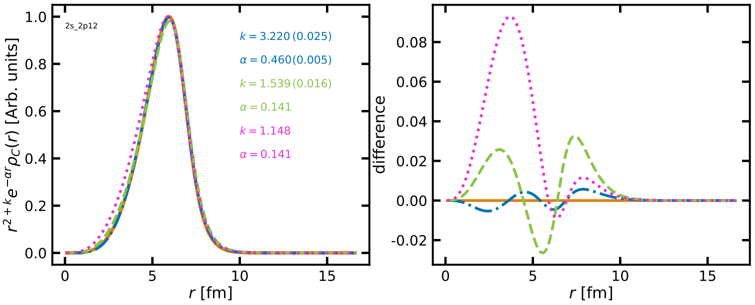

Fig: Konstantin Beyer

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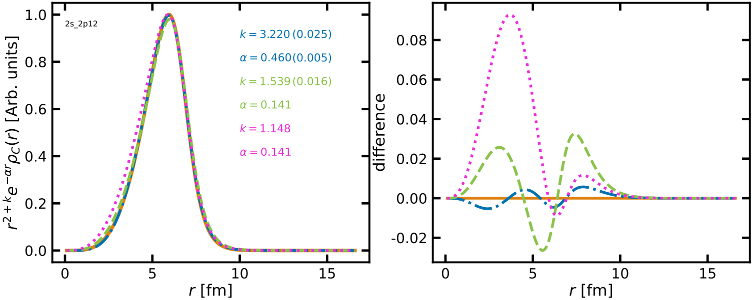

$$R_B = 6.752 \,/\, 6.954 \,/\, 6.881$$

Fig: Konstantin Beyer

V_2 parameter

$$V_2 \equiv \frac{r^e_{\mathrm{rms}}}{B^e_{if}(k,\alpha_B)} = \frac{r^\mu_{\mathrm{rms}}}{B^\mu_{if}(k,\alpha_B)} \qquad \Rightarrow \qquad r^\mu_{\mathrm{rms}} = B^\mu_{if}(k,\alpha_B)V^e_2$$

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$$\frac{\delta V^e_2}{V^e_2} = \sqrt{\left(\frac{\partial V^e_2}{\partial r^e_{\rm rms}} \frac{\delta r^e_{\rm rms}}{V^e_2}\right)^2 + \left(\frac{\partial V^e_2}{\partial B^e_{if}} \frac{\delta B^e_{if}}{V^e_2}\right)^2 + 2\frac{\partial V^e_2}{\partial r^e_{\rm rms}} \frac{\partial V^e_2}{\partial B^e_{if}} \frac{\mathrm{cov}(r^e_{\rm rms}, \delta B^e_{if})}{(V^e_2)^2}}$$

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- For the uncertainty estimation cov matrix is needed

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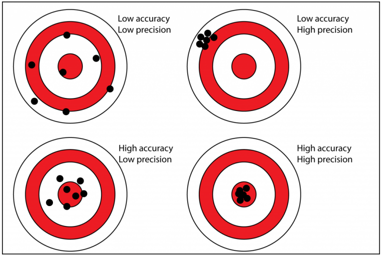
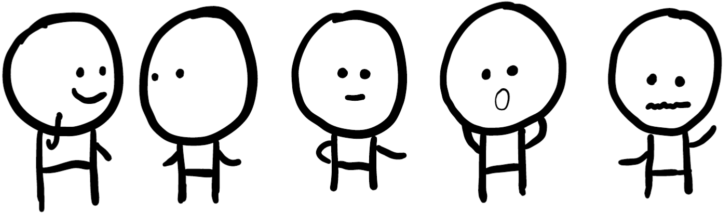


Fig source:

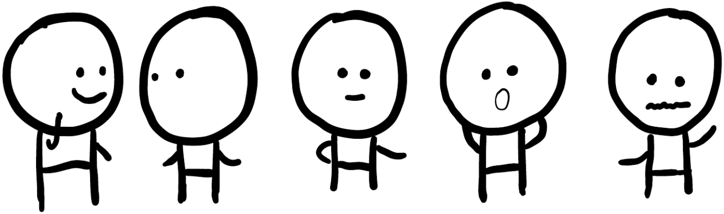
https://www.portaspecs.com/precision-and-accuracy/

Errors propagation over time



Errors propagation over time

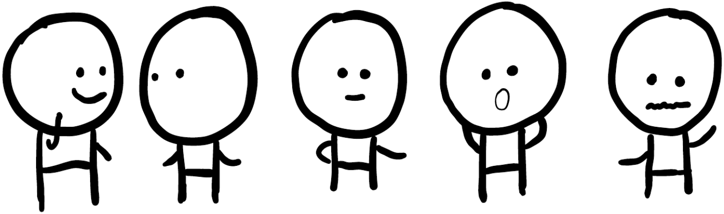
On the
current
level of
accuracy



Errors propagation over time

On the current level of accuracy

an adequate method



Errors propagation over time

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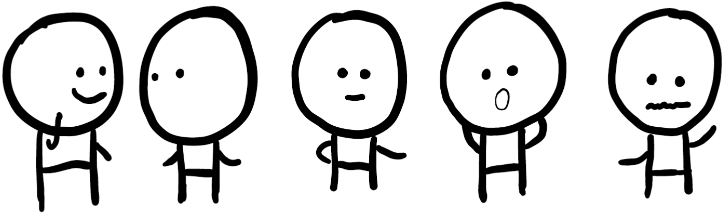

Errors propagation over time

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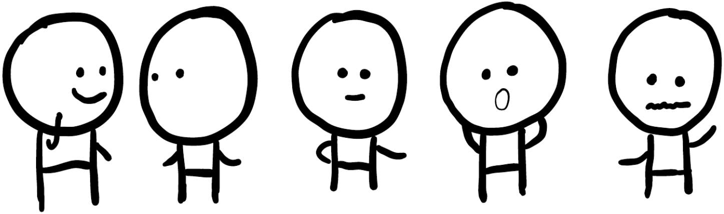
state-of-the-art approach



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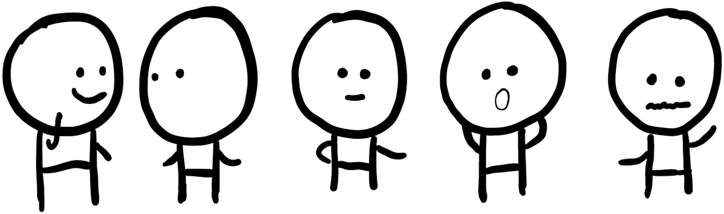


Errors propagation over time

Volume 33B, number 6 PHYSICS LETTERS 23 November 1970

On the current level of accuracy

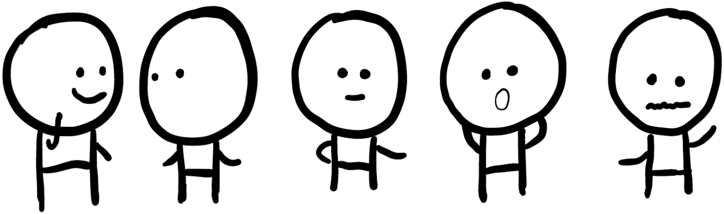
an adequate method

MODEL-INDEPENDENT PARAMETERS OF THE NUCLEAR CHARGE DISTRIBUTION FROM MUONIC X-RAYS

R. C. BARRETT

University of Surrey, Guildford, UK

Received 4 October 1970



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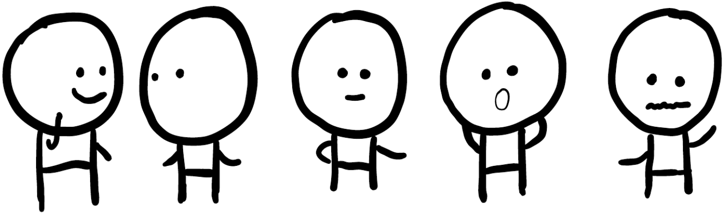

“A method described in details in [1]” (dozens of citations)

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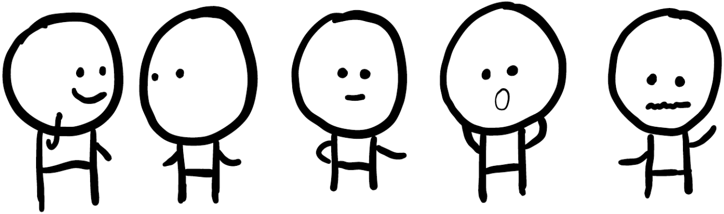

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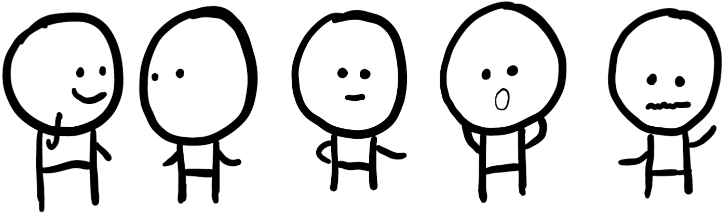
Errors propagation over time

On the current level of accuracy | an adequate method | good approximation | state-of-the-art approach | precise calculations



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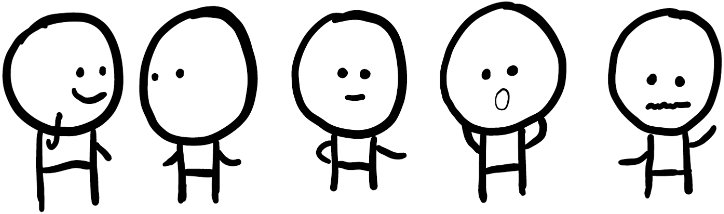

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[2] "applying method presented in [3]"

Cargo Cult Science by RICHARD P. FEYNMAN (1974)

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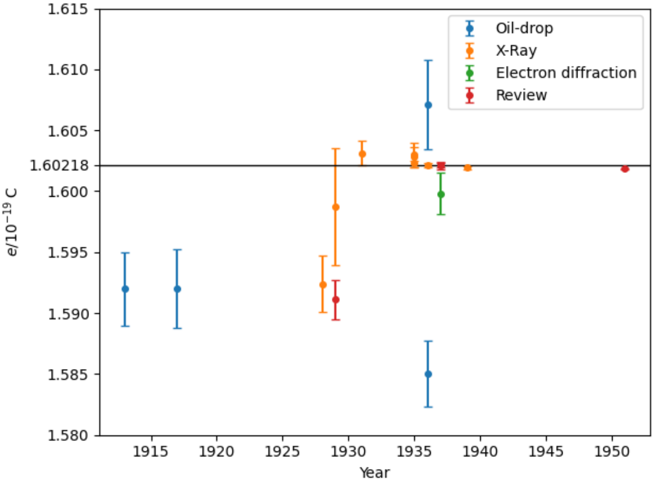

A scatter plot of electron charge measurements as suggested by Feynman, using papers published from 1913–1951 (from wikipedia)

More recent: Proton radius puzzle

$$1\text{fm} = 10^{-15}\text{m} = 0,000\,000\,000\,000\,001\,\text{m}$$

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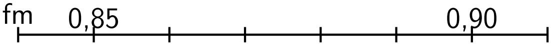

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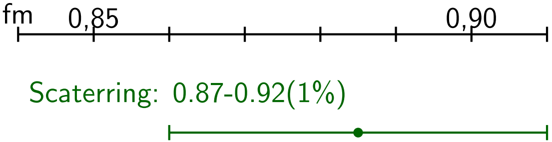

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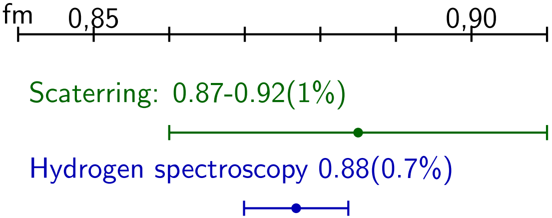

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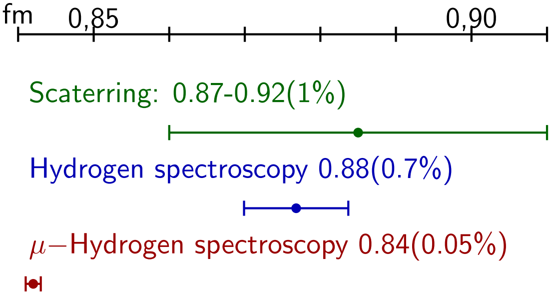

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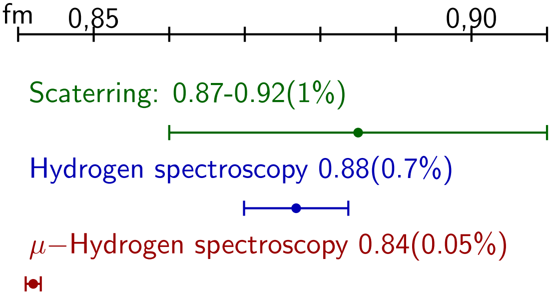

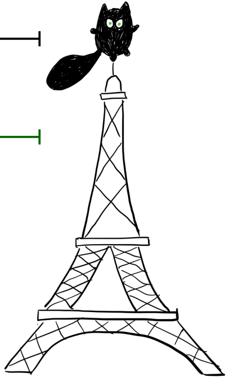

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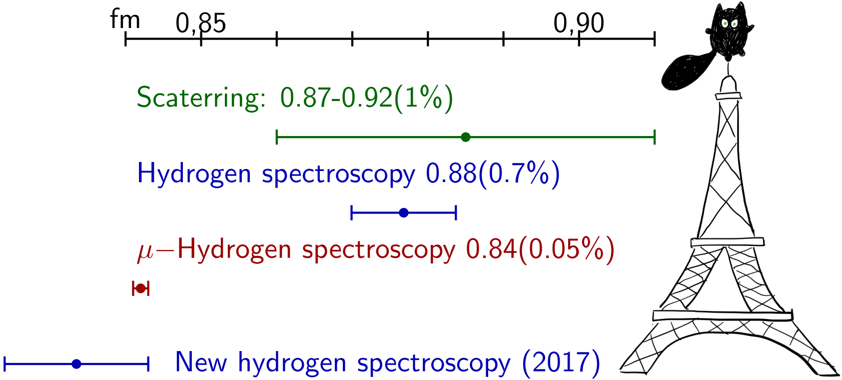

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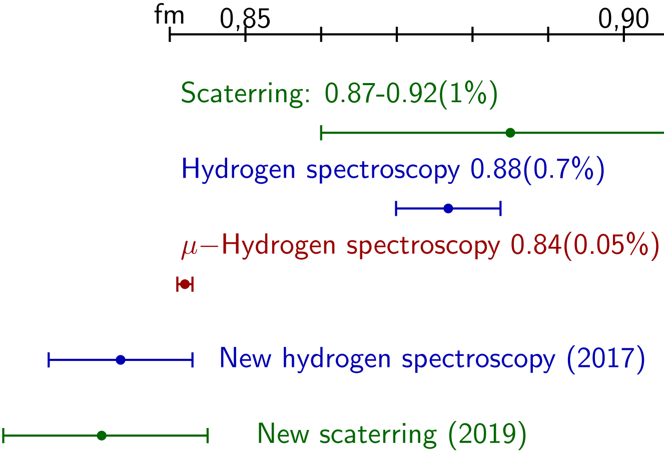
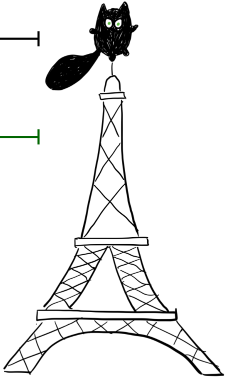
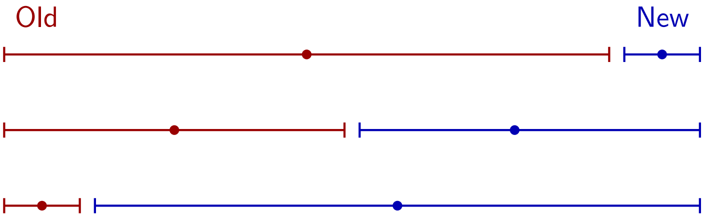




New vs Old: Win or Lose?



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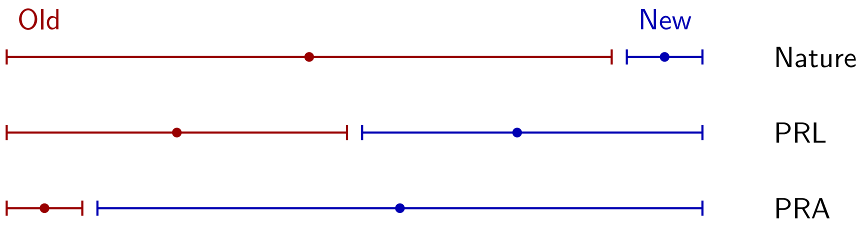

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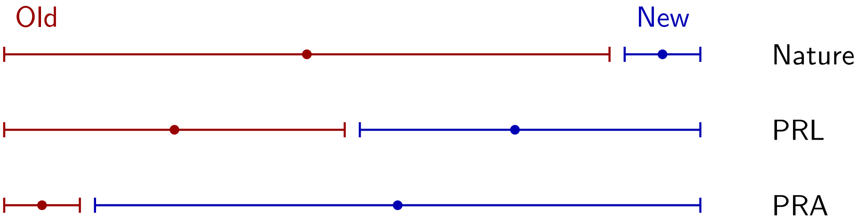

- Only improvements are welcomed

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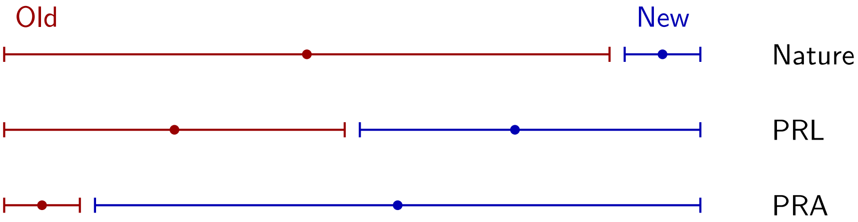

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- Criticism is unpleasant and hard to publish

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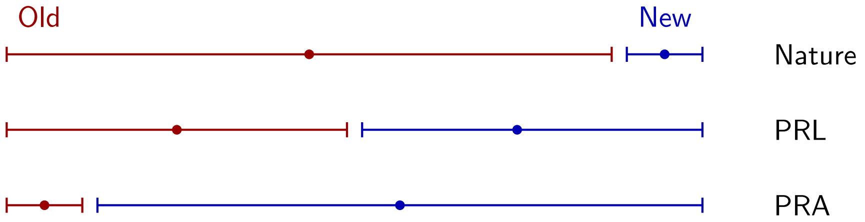
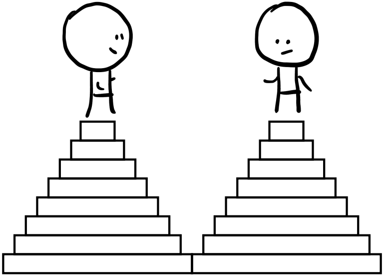
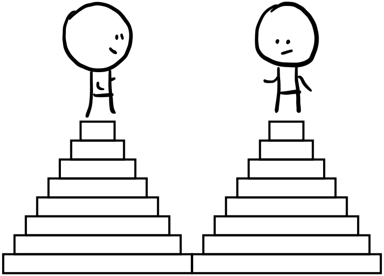


- Only improvements are welcomed
- Criticism is unpleasant and hard to publish
- Be brave, but it can cost you

Interdisciplinarity and reproducibility



Interdisciplinarity and reproducibility



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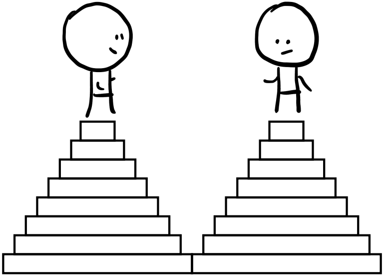
Interdisciplinarity and reproducibility



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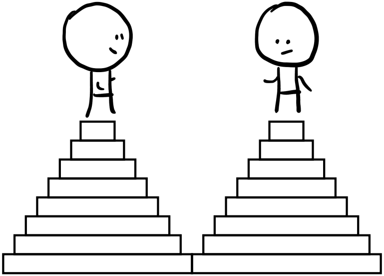
Interdisciplinarity and reproducibility



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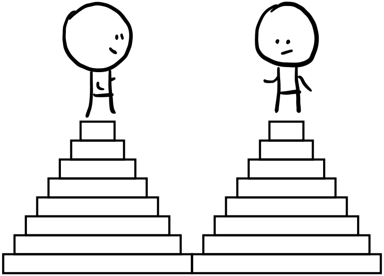

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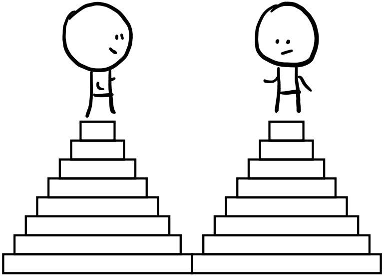

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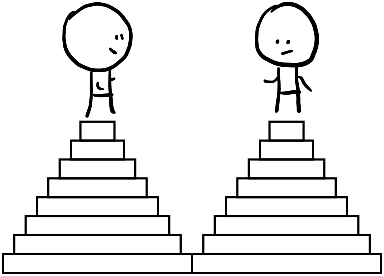

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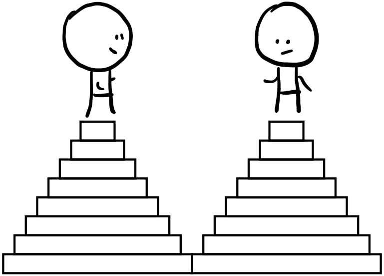
Interdisciplinarity and reproducibility



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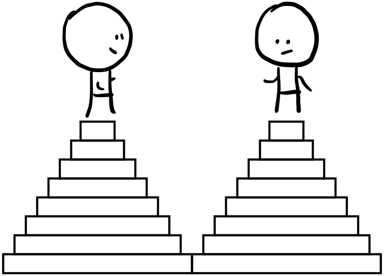
Interdisciplinarity and reproducibility



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- Constants: changing with time!
- Calibration lines: changing with time!
- Hidden raw data
- Omitted details of methods/experiments

Conclusions and outlook

if I will ignore it

maybe it will go away

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