radbase: *Tools for a Modern Evaluation of Nuclear Charge Radii*

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Overview

- IAEA Working Group White Paper Summary
- Objectives for Next Compilation and Evaluation
- radbase: Correlations
- radbase: Network Approach to Data Storage
- Timeline

Highly Charged Ions Talk
Friday 2:30 P.M.

White Paper: Towards Better Nuclear Charge Radii

- Posted on arXiv: 2604.08985:
  - Current status of different techniques.
  - Recommended data to include in publications.
  - Broad framework for next evaluation.

Towards better nuclear charge radii

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Follow-up of 2025 IAEA Technical Meeting

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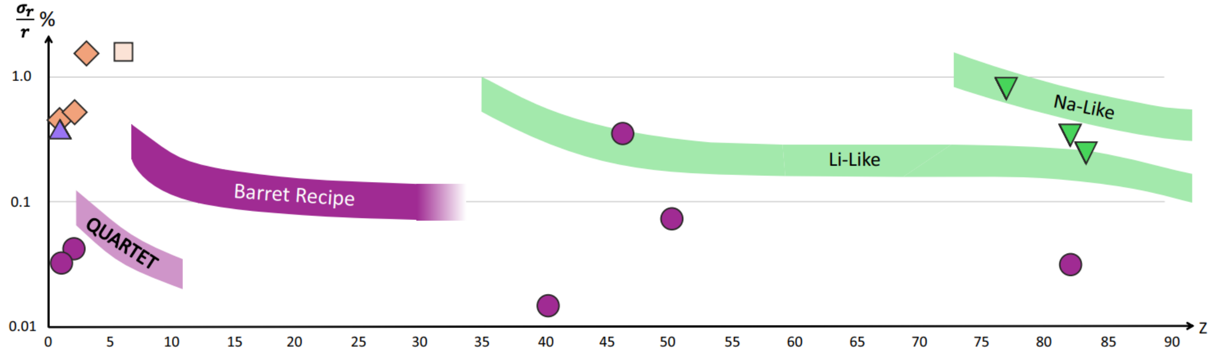
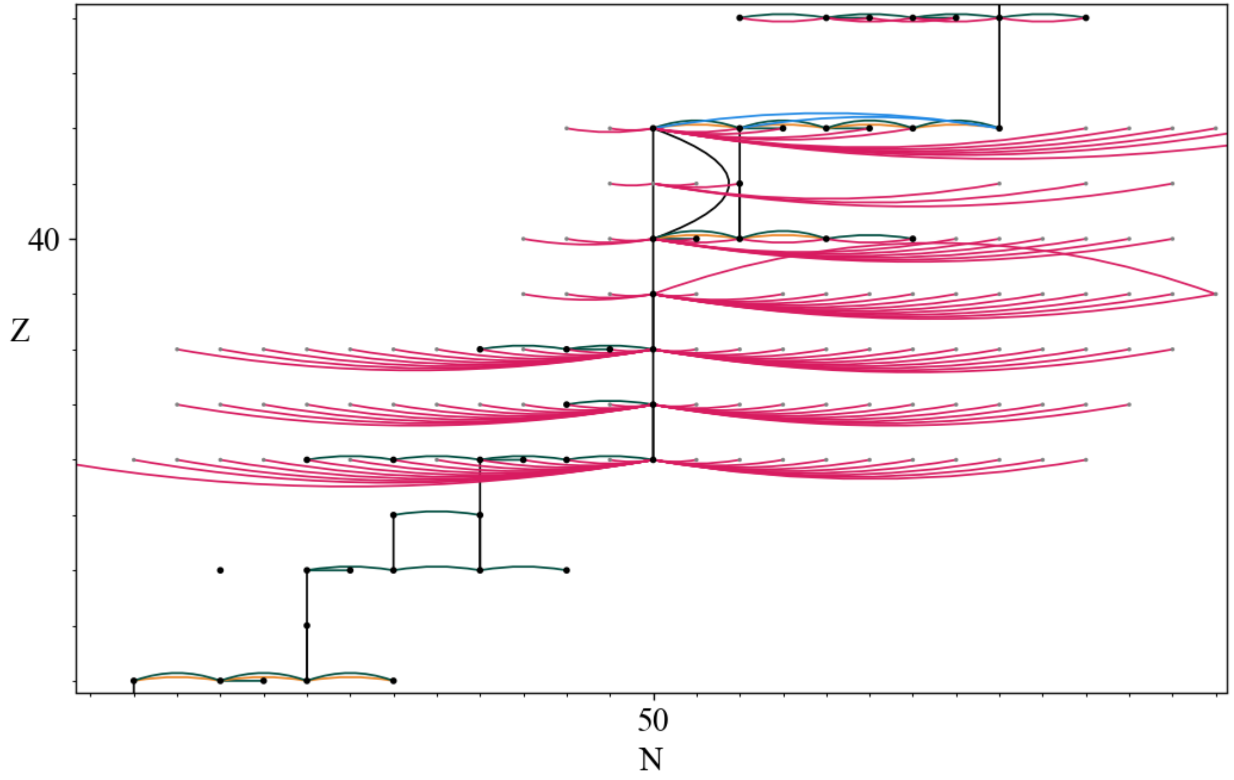


How Do We Measure Nuclear Charge Radii?

- **Absolute** – determines individual charge radii
  - Muonic atom spectroscopy, elastic e^{-}/μ^{-} scattering, g-factor determinations
- **Relative** – determines differences of charge radii
  - Optical isotope-shifts (OIS), Kα isotope shifts, g-factor determinations, highly-charged-ion spectroscopy



Data used in Angeli and Marinova ADNDT 99 69 (2013)

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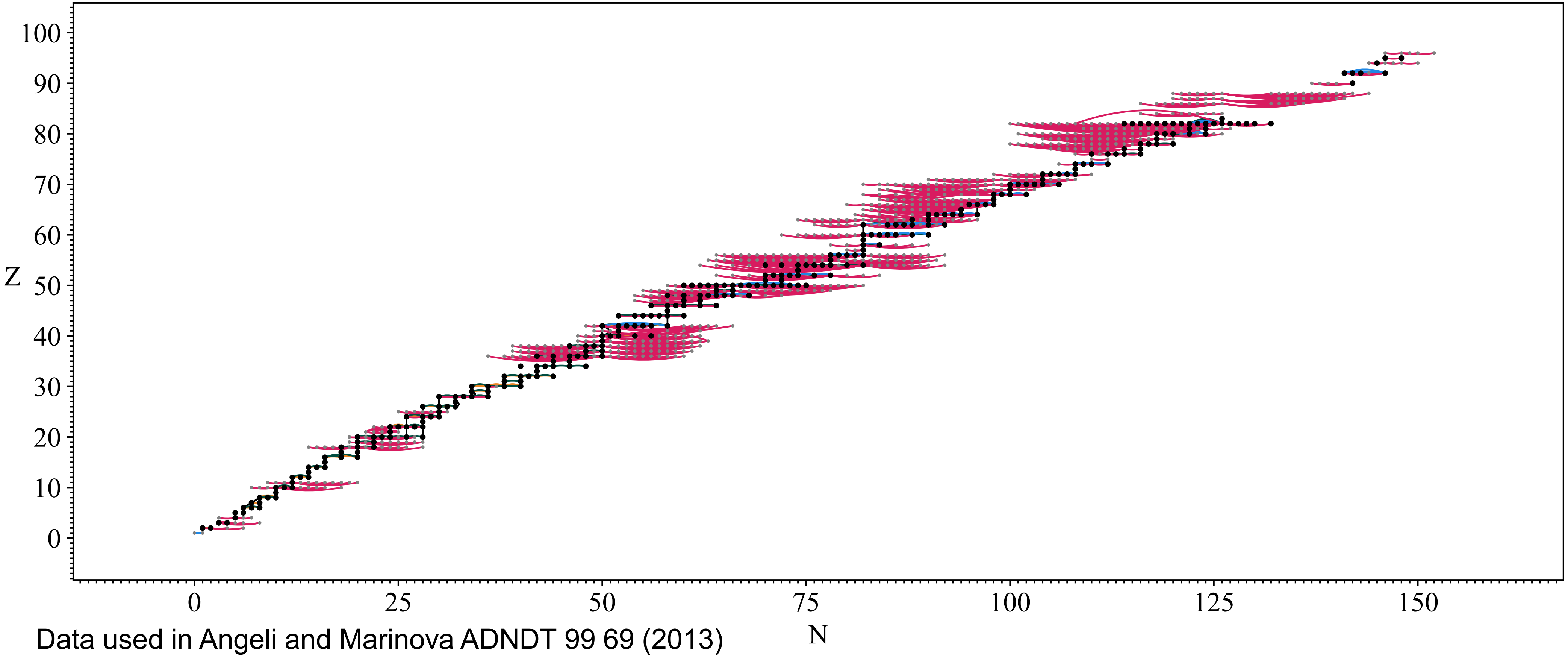
Nuclear Radius Data



Data used in Angeli and Marinova ADNDT 99 69 (2013)

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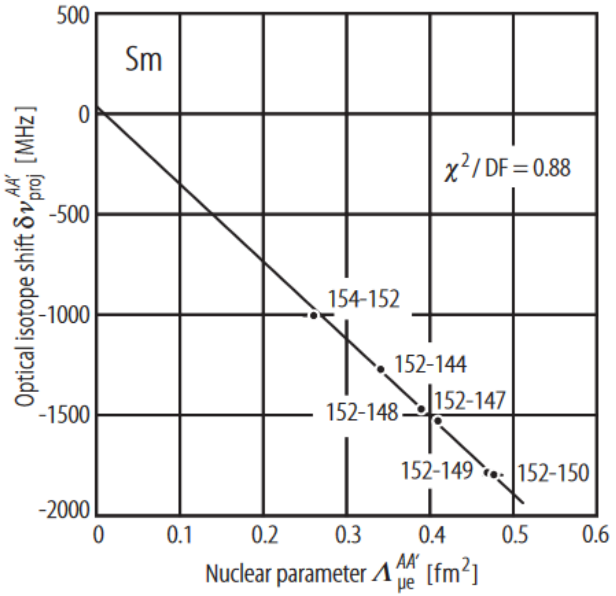
Previous Comprehensive Evaluations

Fricke and Heilig, 2004

1. Comprehensive compilation
2. King Plot focused analysis



18.1.3 Muonic atom data

18.1.3.1 Muonic 2p–1s transition energies, muonic Barrett radii, and model dependent **RMS-radii**

E_{exp}	Experimental muonic atom transition energies (center of gravity of 2p–1s); the error (given in parantheses) is the statistical one.
E_{theor}	Energy of the transition calculated using a two parameter Fermi distribution.
t	Skin thickness fixed at 2.30 fm.
c	Half-density radius fitted to reproduce the experimental transition energy.
$NPol$	Calculated nuclear polarization correction.
$<r^2>^{1/2}_{model}$	RMS charge radius calculated from t and c, model dependent.
$R_{k\alpha}$	Model-independent Barrett equivalent radius; the parameters k and α are fitted to the corresponding transition; the first error is derived from the error of the experimental transition energy; the second error is estimated assuming as an upper limit a 30% error for the nuclear polarization corrections. For more details see Introduction Chapter 4.
C_z	Sensitivity factor $C_z = dR_{k\alpha} / dE$.

A	E_{exp} [keV]	E_{theo} [keV]	$Npol$ [keV]	c [fm]	$<r^2>^{1/2}_{model}$ [fm]	α [1/fm]	k	C_z [10^{-3}fm/eV]	$R^{\mu}_{k\alpha}$ [fm]	Ref.
36	644.597(24)	644.597	0.118	3.5845(18)	3.390	0.0548	2.0821	–0.060	4.3515(14;21)	FMS82
	644.34(0.11)		0.130	3.711(6)	3.402	0.062	2.215		4.3668(8)	PD76[1])
38	644.434(24)	644.432	0.107	3.6025(17)	3.402	0.0547	2.0822	–0.060	4.3664(14;19)	FMS82
	644.13(0.16)		0.130	3.690(9)	3.415	0.062	2.215		4.385(11)	PD76[1])
40	644.004(25)	644.000	0.126	3.6416(18)	3.427	0.0546	2.0827	–0.060	4.3986(15;23)	FMS82
	643.94(0.11)		0.130	3.670(6)	3.429	0.062	2.215		4.403(8)	PD76[1])

Previous Comprehensive Evaluations

Angeli 2004

1. Weighted least squares fit
2. Internal and external uncertainties considered

Table 1
Nuclear rms charge radii. (For the neutron the entry is $\langle r^2 \rangle$ (fm^2) and for the proton and deuteron, see Section 2.) See page 194 for Explanation of Tables

Z	El	A	R (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
0	n	1	−0.1149	.0024	
1	H	1	0.8791	.0088	
		2	2.1402	.0091	
		3	1.7591	.0356	
2	He	3	1.9448	.0137	
		4	1.6757	.0026	
3	Li	6	2.5385	.0267	
		7	2.4312	.0281	

Radius data and techniques found in previous works:

INTERNATIONAL ATOMIC ENERGY AGENCY
INDC(HUN)-033
Distr.: ND+G
INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

TABLE OF NUCLEAR ROOT MEAN SQUARE CHARGE RADII*

Hyperfine Interactions **136**: 17–24, 2001. 17
© 2002 *Kluwer Academic Publishers. Printed in the Netherlands.*

Comparison of the *Seltzer* Coefficient C_1 to Experimental Data

Previous Comprehensive Evaluations

Angeli and Marinova 2013

1. Angeli04 + Nadjakov94
2. Current IAEA NDS recommendation

Z	Elem.	Mass	n	R_{av}(fm)	ΔR_{av}(fm)
0	n	1	1	-0.1149	0.0027
1	H	1	0	0.8783	0.0086
		2	1	2.1421	0.0088
		3	2	1.7591	0.0363
2	He	3	1	1.9661	0.0030
		4	2	1.6755	0.0028
		6	4	2.0660	0.0111
		8	6	1.9239	0.0306

IAEA Working Group on Nuclear Charge Radii

Long Term Objectives - Compilation

Compilation of Charge Radius Data

- Includes experimental and theoretical inputs required to reconstruct radii.
- Relies on original data, not secondary sources
- Updated frequently (once a month)
- Accessible via web-interface

Item	Input value		Adjusted value		v_i	Dg
^{126}Ag−u	−65926	329	−65190#	220#	0.9	D
$C_{10}H_6-^{126}$Te	143623	9	143638.0	1.5	0.7	U
	143640	8			−0.2	U
^{126}Xe−u	−95647	30	−95702.578	0.006	−1.9	U
^{126}Cs−u	−90543	49	−90554	11	−0.2	U
^{126}Ba−u	−88745	30	−88750	13	−0.2	R
^{126}La−u	−80503	232	−80490	100	0.1	2
^{126}Ce−u	−76029	30				2
$^{126}Xe-^{134}Xe_{.940}$	−6772.8	2.9	−6772.026	0.004	0.3	o
	−6773.2	3.8			0.3	1

Image Credit: W. J. Huang et al. Chinese Physics C 45 03002 (2021)

Recommended† magnetic dipole moments

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Method	Recommended Tables
^{28}Si	1779	0.48 ps	2+	+1.1(2)	IMPAC	INDC(NDS)-0816

Recommended† electric quadrupole moments

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	Q [b]	Method	Recommended Tables
^{28}Si	1779	0.48 ps	2+	+0.16(3)	CER	INDC(NDS)-0833

Compiled‡ magnetic dipole and electric quadrupole moments from published articles

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Q [b]	Ref. Std	Method	NSR keyword
^{28}Si	1779	0.49 ps	2^+	+1.1(2)			IMPAC	1975EB01
					+0.16(3)		CER , R	1981SP07
					+0.18(3)		CER	1980BA40
					+0.16(3)		CER	1980SP09

Image Credit: IAEA NDS Nuclear Electromagnetic Moments Database

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Long Term Objectives - Evaluation

Comprehensive Critical Evaluation

- Constructed by experts from different techniques
- Correlations between charge radii considered
- Analysis decisions fully transparent
- Output covariance matrix provided

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The AME 2020 atomic mass evaluation (II). Tables, graphs and references*

To cite this article: Meng Wang *et al* 2021 *Chinese Phys. C* **45** 030003

Recommended† magnetic dipole moments

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Method	Recommended Tables
^{28}Si	1779	0.48 ps	2+	+1.1(2)	IMPAC	INDC(NDS)-0816

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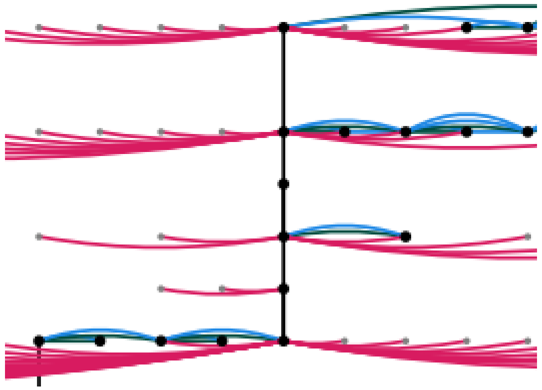
					+0.16(3)		CER , R	1981SP07
					+0.18(3)		CER	1980BA40
					+0.16(3)		CER	1980SP09

Image Credit: IAEA NDS Nuclear Electromagnetic Moments Database

radbase – Backend for Evaluation/Compilation

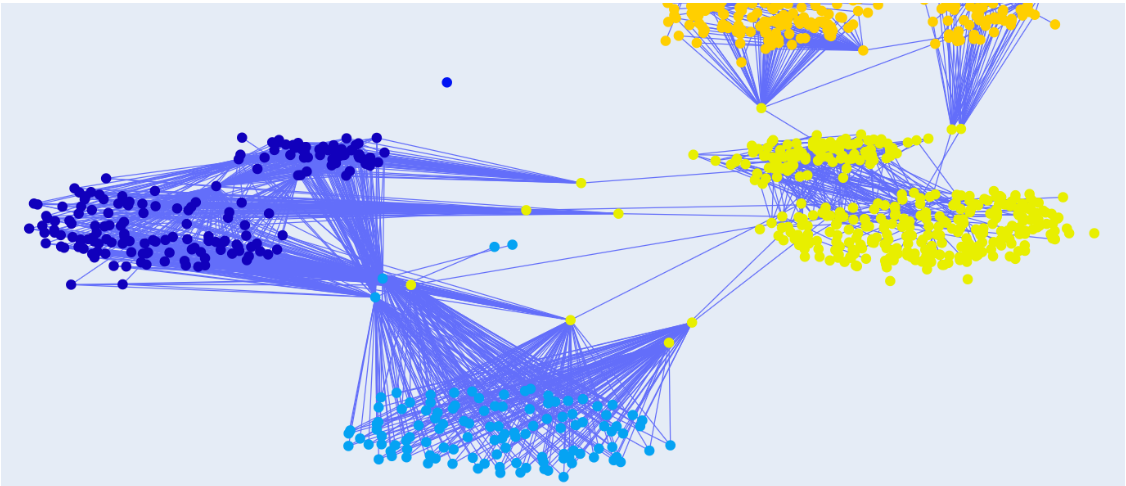
radbase Public

```
Total Nuclides: 229
Primary Nuclides: 79
Primary Measurements:
Id 263: R050110 = 4.5807 +/- 0.0064
Id 264: R050111 = 4.5859 +/- 0.0061
```



Goals:

- Storage of data in consistent, computer readable format
- Correlation propagation
- Search and visualization of data



Definitions

- Input Data: experimental and theoretical information needed to obtain radii
- Output Data: charge radii or intermediate quantities obtained from inputs.
- Conversion: the process of converting inputs to charge radius data

Statistical Correlations

- Largest change to next evaluation: <u>inclusion of statistical correlations between charge radius data.</u>

- Correlations shift recommended radii values, uncertainties, and covariances.

- Particularly impactful when absolute and relative radius information is combined.

```
Id 0: R030064 = 4.1540 +/- 0.0030
Id 1: R030066 = 4.1870 +/- 0.0030
Id 2: R030067 = 4.2000 +/- 0.0030
Id 3: R030068 = 4.2400 +/- 0.0030
Id 4: R030066**2-R030064**2 = 0.2753 +/- 0.0001
Id 5: R030067**2-R030066**2 = 0.1090 +/- 0.0001
Id 6: R030068**2-R030067**2 = 0.3376 +/- 0.0001
```

Absolutes are independent ($\rho = 0$)

```
Id 0: R030064 = 4.1537 +/- 0.0015
Id 1: R030066 = 4.1867 +/- 0.0015
Id 2: R030067 = 4.1997 +/- 0.0015
Id 3: R030068 = 4.2397 +/- 0.0015
```

Absolutes are correlated ($\rho = 0.7$)

```
Id 0: R030064 = 4.1529 +/- 0.0027
Id 1: R030066 = 4.1859 +/- 0.0026
Id 2: R030067 = 4.1989 +/- 0.0026
Id 3: R030068 = 4.2389 +/- 0.0026
```

Statistical Correlations

To include correlations between charge radii you need to:

1. Determine correlations between input data
2. Propagate these correlations to the charge radii
3. Optimize recommended radii, considering correlations

Generally, difficulty decreases as you go from 1 to 3.

1.) Input Data Correlation – Sources

Sources of correlation:

- Experimental – sometimes reported, can often be estimated.
- Theoretical – almost never reported, likely the largest source of correlation between charge radius data
- Shared Data / Interpolation – most transparent, can be determined by evaluators.

1.) Input Data Correlations – Exp. Sources

- Listed experimental correlation information is local (only for a few nuclides).
- Complete correlation information is sometimes available.
- Can be estimated with understanding of technique.

					^{55}Mn	^{54}Cr	^{53}Cr	^{52}Cr	^{50}Cr	^{51}V	^{50}Ti	^{49}Ti	
^{41}K	−0.349 24												
^{40}Ca	71.062 41	71.411 38			84.188 29	167.154 29	165.661 33	164.756 30	165.864 32	244.841 35	323.454 35	323.616 38	^{56}Fe
^{42}Ca	70.251 43	70.600 40	−0.811 16			82.966 28	81.473 32	80.568 29	81.676 33	160.653 34	239.266 32	239.428 35	^{55}Mn
^{43}Ca	70.693 42	71.042 39	−0.369 15	0.442 16			−1.493 22	−2.398 20	−1.290 27	77.687 30	156.300 31	156.462 35	^{54}Cr
^{44}Ca	70.038 41	70.387 38	−1.024 13	−0.213 16	−0.655 14			−0.905 19	0.203 28	79.180 26	157.793 30	157.955 34	^{53}Cr
^{46}Ca	70.699 110	71.048 111	−0.363 105	0.448 106	0.006 106	0.661 106			1.108 22	80.085 24	158.698 27	158.860 30	^{52}Cr
^{48}Ca	71.369 41	71.718 38	0.307 12	1.118 15	0.676 16	1.331 14	0.670 106			78.977 31	157.590 34	157.752 36	^{50}Cr
^{45}Sc	143.877 43	144.226 40	72.815 32	73.626 34	73.184 33	73.839 32	73.178 109	72.508 33			78.613 31	78.775 34	^{51}V
^{46}Ti	218.876 41	219.225 38	147.814 29	148.625 32	148.183 31	148.838 30	148.177 108	147.507 30	74.999 29			0.162 27	^{50}Ti
^{47}Ti	219.356 41	219.705 38	148.294 29	149.105 32	148.663 31	149.318 30	148.657 108	147.987 31	75.479 29	0.480 19			
^{48}Ti	219.534 41	219.883 38	148.472 32	149.283 33	148.841 31	149.496 32	148.835 109	148.165 33	75.657 32	0.658 23	0.178 19		
^{49}Ti	220.308 46	220.657 43	149.246 36	150.057 38	149.615 37	150.270 37	149.609 110	148.939 37	76.431 36	1.432 29	0.952 25	0.774 27	
^{50}Ti	220.470 41	220.819 38	149.408 31	150.219 33	149.777 32	150.432 31	149.771 109	149.101 32	76.593 32	1.594 23	1.114 22	0.936 22	
^{51}V	299.083 41	299.432 38	228.021 36	228.832 38	228.390 36	229.045 36	228.384 110	227.714 36	155.206 35	80.207 35	79.727 34	79.549 35	
^{50}Cr	378.060 42	378.409 39	306.998 37	307.809 39	307.367 38	308.022 38	307.361 111	306.691 39	234.183 37	159.184 37	158.704 35	158.526 37	
^{52}Cr	379.168 38	379.517 35	308.106 33	308.917 35	308.475 33	309.130 33	308.469 110	307.799 33	235.291 32	160.292 32	159.812 30	159.634 31	
^{53}Cr	378.263 41	378.612 38	307.201 35	308.012 36	307.570 35	308.225 35	307.564 110	306.894 35	234.386 35	159.387 34	158.907 33	158.729 34	
^{54}Cr	376.770 45	377.119 42	305.708 35	306.519 37	306.077 36	306.732 35	306.071 111	305.401 36	232.893 35	157.894 35	157.414 33	157.236 35	
^{55}Mn	459.736 46	460.085 45	388.674 35	389.485 36	389.043 35	389.698 35	389.037 110	388.367 35	315.859 31	240.860 33	240.380 30	240.202 34	
^{56}Fe	543.924 41	544.273 38	472.862 35	473.673 38	473.231 37	473.886 36	473.225 110	472.555 36	400.047 36	325.048 36	324.568 35	324.390 36	
	^{39}K	^{41}K	^{40}Ca	^{42}Ca	^{43}Ca	^{44}Ca	^{46}Ca	^{48}Ca	^{45}Sc	^{46}Ti	^{47}Ti	^{48}Ti	

Wohlfahrt et. al. PRC (23) 1, 1981

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1.) Input Data Correlations – Theory Sources

- Positive examples from muonic atom spectroscopy theory
  - Enough information to reconstruct local correlations.

Isotope	Transition	Nuclear	Nucleon	Total	f_{Corr} (%)
^{35}Cl	$2p1s$	103(24)	11.9(1.2)	115(25)	90.4
	$3p1s$	104(24)	11.9(1.2)	116(26)	90.4
	$4p1s$	104(24)	11.9(1.2)	116(26)	90.4
^{37}Cl	$2p1s$	99(23)	12.6(1.3)	115(25)	97.6
	$3p1s$	100(23)	12.6(1.3)	116(26)	97.6
	$4p1s$	100(23)	12.6(1.3)	116(26)	97.6

Cl35-Cl37 Beyer et al., arXiv:2506.08804

More work to do!

Currently building *radbase* to prepare for better correlations.

State	KDE0	SKX	SLy5	BSk14	SAMi	NRAPR	SkP	SkM*	SGII	avg.(range)
$1s_{1/2}$	-5463	-5432	-5557	-5588	-5727	-5889	-5815	-5905	-6035	-5712(603)
$2s_{1/2}$	-1021	-970	-1048	-1030	-1045	-1095	-1116	-1112	-1126	-1063(156)
$2p_{1/2}$	-1781	-1850	-1834	-1900	-1937	-1997	-1955	-2005	-2044	-1923(263)
$2p_{3/2}$	-1725	-1798	-1776	-1852	-1877	-1936	-1886	-1942	-1981	-1864(256)
$3p_{1/2}$	-529	-576	-556	-566	-616	-540	-628	-614	-627	-584(99)
$3p_{3/2}$	-559	-612	-589	-602	-648	-576	-672	-645	-664	-619(96)
$3d_{3/2}$	-221	-268	-219	-252	-225	-212	-268	-248	-230	-238(56)
$3d_{5/2}$	-23	-29	-33	-21	-47	-58	-40	-35	-49	-37(37)

Pb208 NP - Sun et al., PRL (135) 163002 2025

Network View of Radius Data

- Radii depend on quantities which depend on quantities which …
- Abstractly, this can be represented by a directed graph – quantities are nodes, dependencies are directed edges.

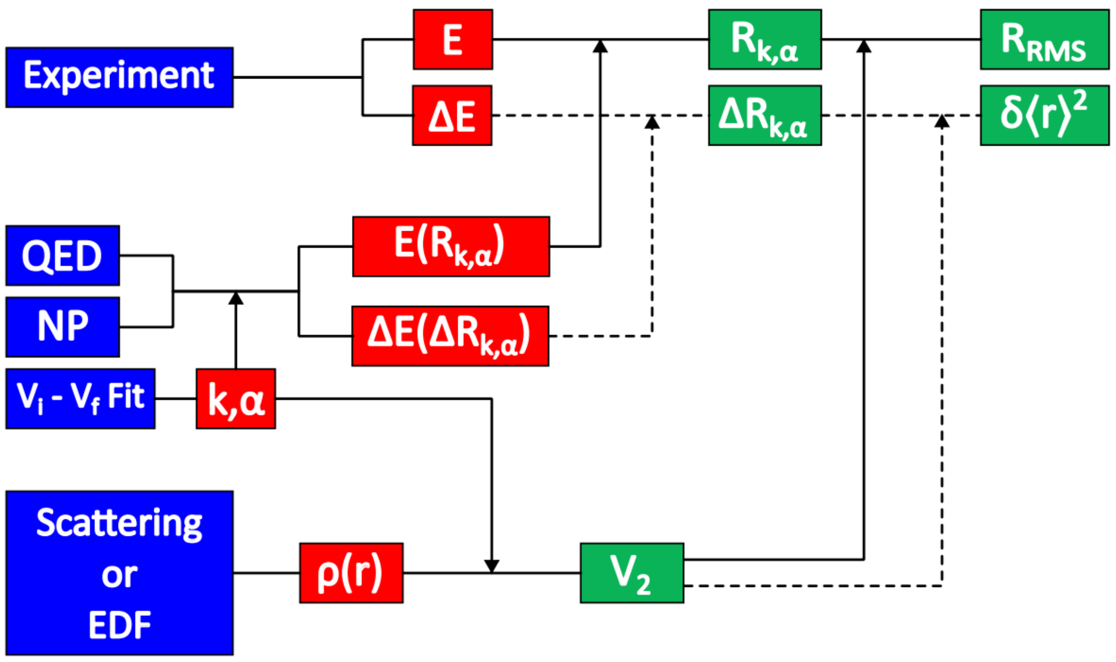
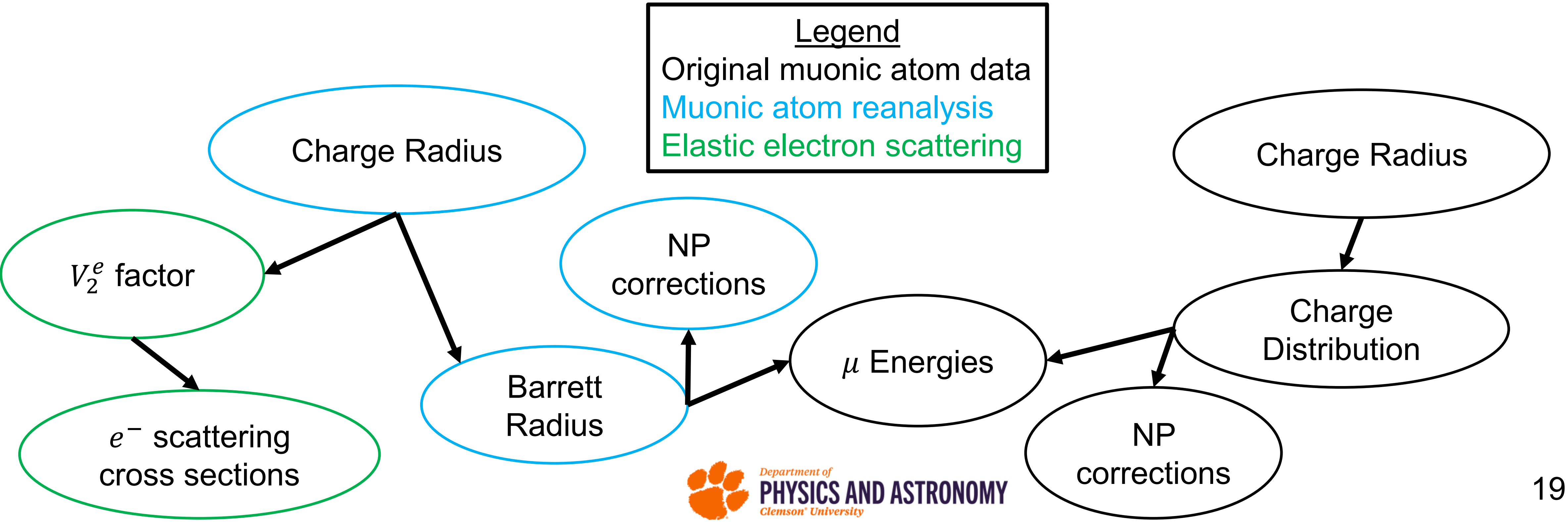


Image Credit: Beyer et al., arXiv:2506.08804

Network View of Radius Data

- Allows radii to be traced back to source information.
- Reanalysis can be included alongside original data.



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Functions vs. Quantities

Conversion maps inputs to outputs:

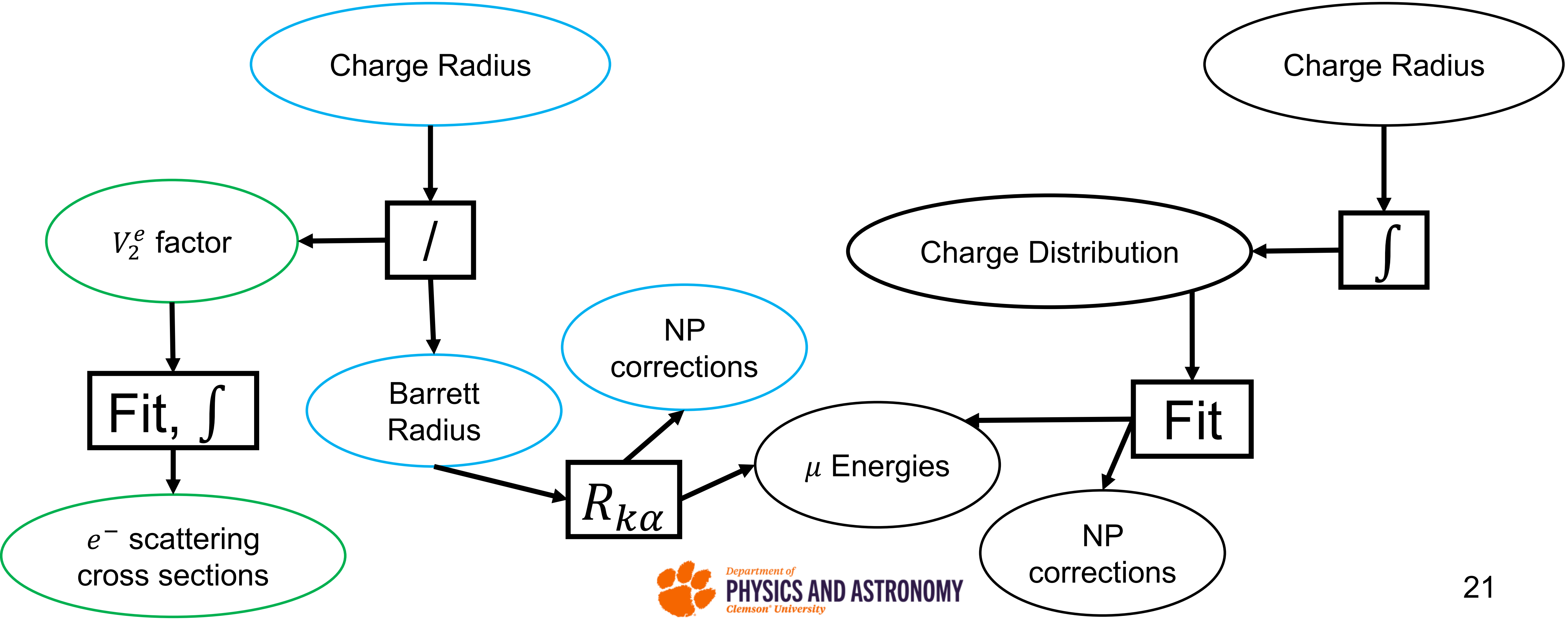
$$Q_{out} = C(Q_{in})$$

Two separate pieces of information with a conversion step:

1. What is the converted quantity? $R_c = 4.82(3)\ \text{fm}$
2. What is the conversion function? $R_c\left(R^{\mu}_{k\alpha}, V^e_2\right) = \frac{R^{\mu}_{k\alpha}}{V^e_2}$

Importantly, you need the conversion function to propagate correlations.

Conversion Functions – Network View



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Conversion Functions

- Some steps provide the function, while others do not.

$$R_c\left(R^{\mu}_{k\alpha}, V^e_2\right) = \frac{R^{\mu}_{k\alpha}}{V^e_2}$$

- Transparent (Differentiable) vs. Opaque (Not Differentiable)

$$R^{\mu}_{k\alpha}\left(\mathrm{E}^{\mathrm{M}}, \mathrm{E}^{\mathrm{NP}}, \mathrm{E}^{\mathrm{QED}}; \mathrm{R}^{\mu}_{\mathrm{k}\alpha,0}, \mathrm{E}_0, \mathrm{C_Z}\right) = \mathrm{R}^{\mu}_{\mathrm{k}\alpha,0} + \mathrm{C_Z}[(E^{M} - E^{NP} - E^{QED}) - \mathrm{E}^0]$$

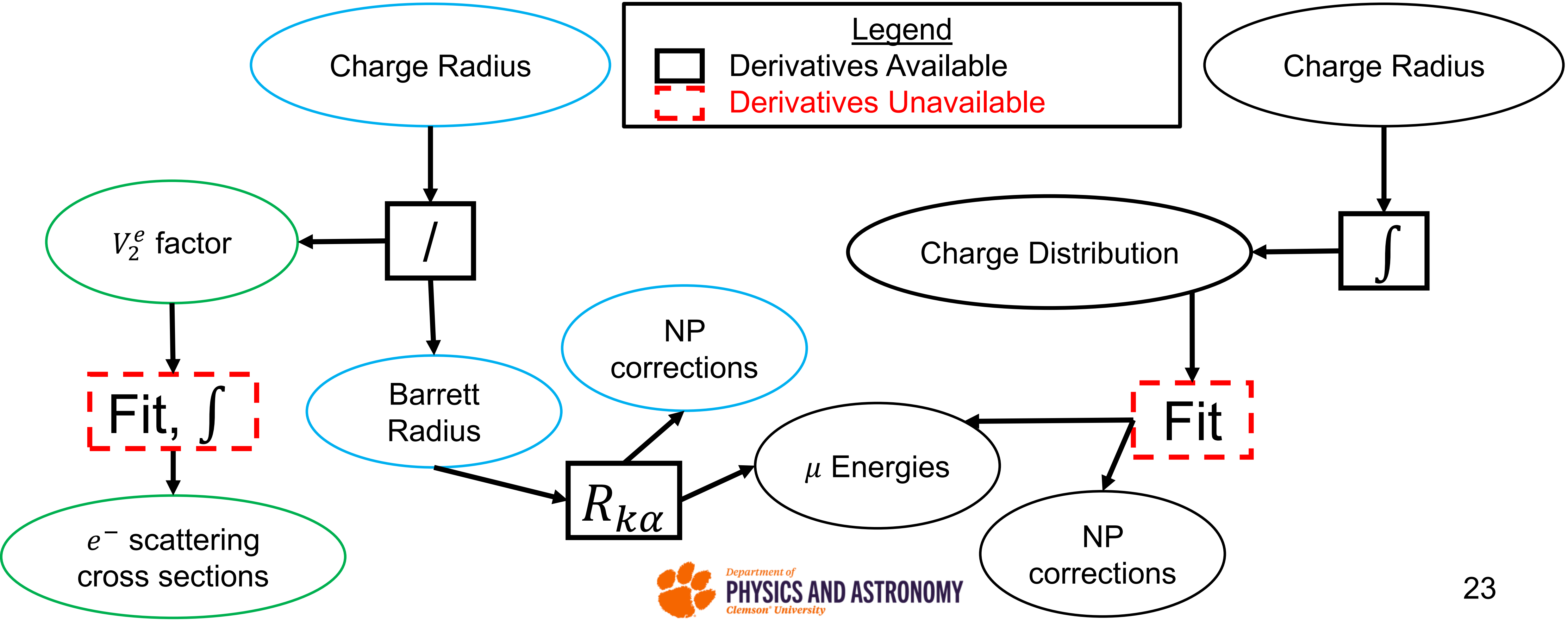
- Can that step be evaluated with new inputs?

Fit to two parameter Fermi shape

$c(E^{M}, E^{NP}, E^{QED})$

$t(E^{M}, E^{NP}, E^{QED})$

Conversion Functions – Network View



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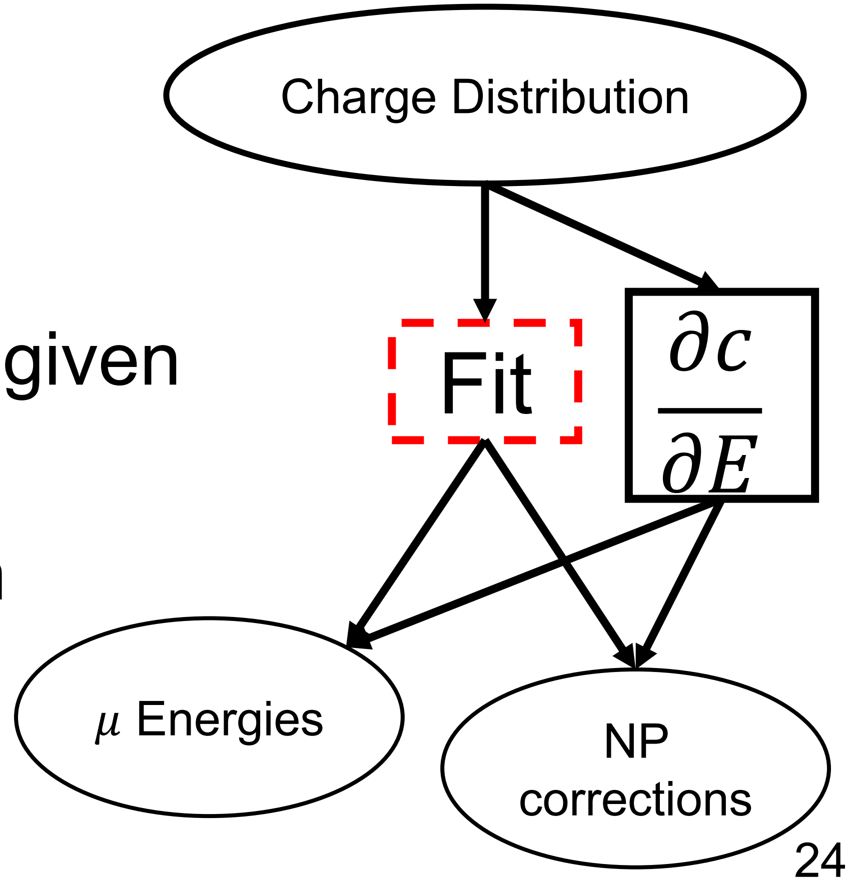
Conversion Functions – Ranking

Best to worst case:

1. Conversion function is provided!
   - Or an approximation (fit Jacobian, polynomial)

2. No function, but correlations are explicitly given

3. No function and no correlation information



2.) Propagating Correlations – Implementation

- *sympy* allows for symbolic manipulation
- *uncertainties* (or *sympy*) to numerically propagate covariances

$$R = R$$

```
Substitute shape: R = R_ka / V_2
```

$$R = \frac{R_{k\alpha}}{V_2}$$

```
Substitute R_ka = R_ka^0 + C_z * (E - E^0)
```

$$R = \frac{C_z \left(E - E^0\right) + R_{k\alpha}^0}{V_2}$$

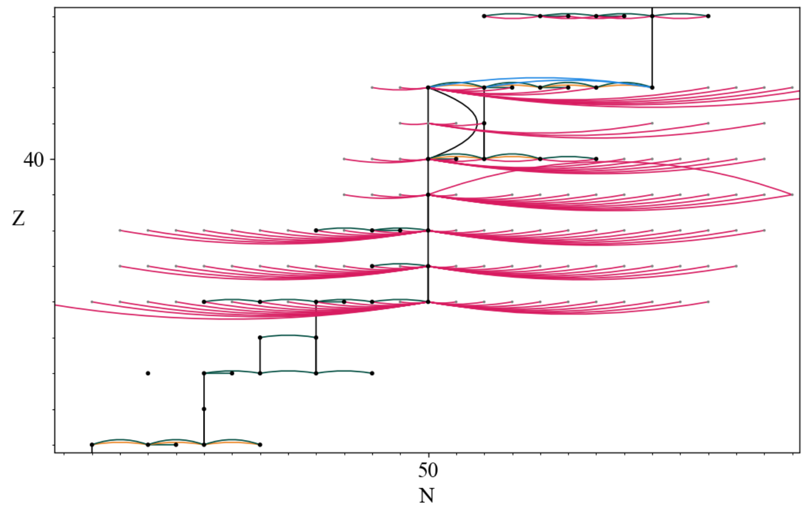
```
from uncertainties import ufloat

uR_ka0, uE = ufloat(5.614, 0.001), ufloat(5126, 0.01)
uV_2 = ufloat(1.095, 0.001)
rad = lambdify([C_z, R_ka0, E, E0, V_2],
               rad,
               modules='numpy')(1e-2, uR_ka0, uE,
                                uE.n, uV_2)
```

$$R = 5.127\text{+/-}0.005$$

3.) Optimization with Correlated Data

- Generalized least squares propagates correlations from radius data
- Implemented in *radbase* alongside optimizations from graph analysis.



Uncorrelated – Weighted Least Squares

$$S = \min_{\beta} \sum_i \left[\frac{y_i - f(x_i,\beta)}{\sigma_i}\right]^2$$

Correlated Errors – Generalized Least Squares

$$S_{\mathrm{GLS}} = \min_{\beta} \left(\boldsymbol{y} - f(\boldsymbol{X},\beta)\right)^T \Omega^{-1} \left(\boldsymbol{y} - f(\boldsymbol{X},\beta)\right)$$

Potential Pitfalls – Correlated Variables

- Numerical errors from highly correlated variables:
  - Ex: Radii from optical isotope shift where atomic theory is dominant uncertainty.
  - Inversion of covariance matrix becomes unstable.

Potential solution: Take CODATA approach, have free parameters besides radii.

Decision to just use radii vs. parameters included in conversion process.

Potential Pitfalls – Non-Gaussian Errors.

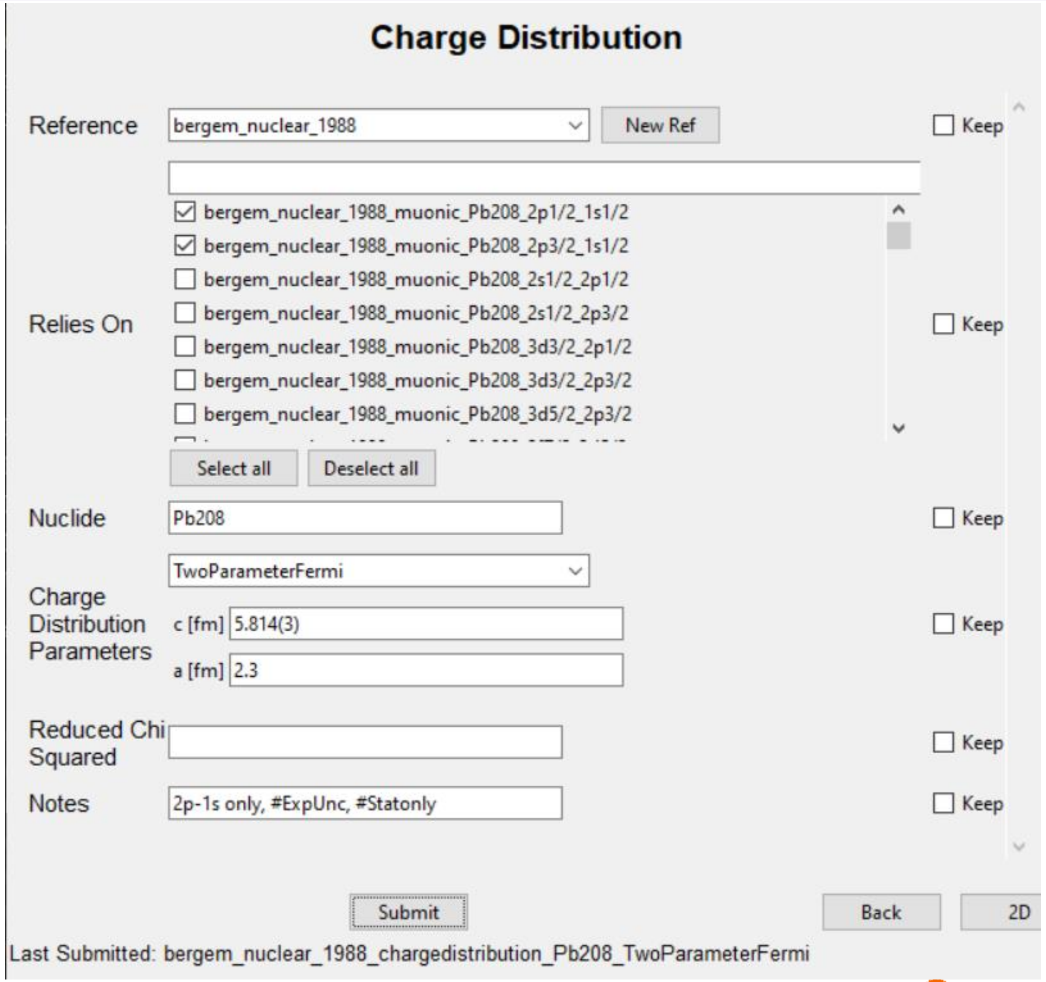
- Some radius data are highly asymmetric/non-normal.
  - Ex. $R_{\mathrm{Pd108}} = 4.537^{+27}_{-6}$ fm

Saito et al. PRC 111 034313 (2025)

Store lower/upper uncertainties then either:

- Transform data to normal errors
- Conservatively use larger of the two.

Data Collection Progress

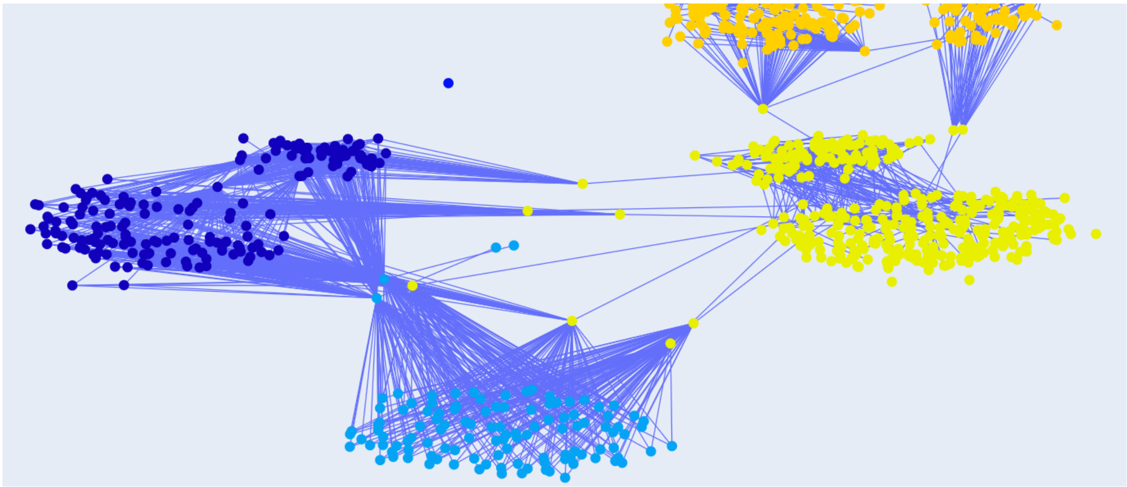


- January 2026, I created a data entry user interface to standardize the entered data.
- Each data type has a template that can dynamically generate its data entry interface.
- Data can be entered programmatically using these templates as well.

Data Collection Progress

- Our group has entered 30 papers since January, focusing on muonic atom spectroscopy papers (most muonic transition energies $6 \leq Z < 50$ from Fr04).

- Rough estimate, ≈150 absolute papers, ≈400 relative papers.



Network of Data near Wohlfahrt PRC 23 533 (1981)

Timeline - 2026

Summer 2026

1. Collect all published absolute nuclear charge radius data
   - $(Z > 2)$
2. Transition from just tracking dependencies to explicit conversion steps.

Fall 2026

1. Complete automated correlation propagation procedure with strong logging.
2. Develop documentation around *radbase*

Timeline - 2027

Fall 2026

1. Complete automated correlation propagation procedure with strong logging.
2. Develop documentation around *radbase*

Spring 2027

1. Collect all published relative nuclear charge radius data ($Z > 2$)
2. Begin working with IAEA on website for search and visualization.

Is *radbase* useful to you today?

No

Will *radbase* be useful to you 6 months from now?

Yes

Conclusions

- Moving towards new comprehensive compilation and evaluation
- Data compilation and standardization
- Inclusion of correlations between inputs

Thank you! Questions?

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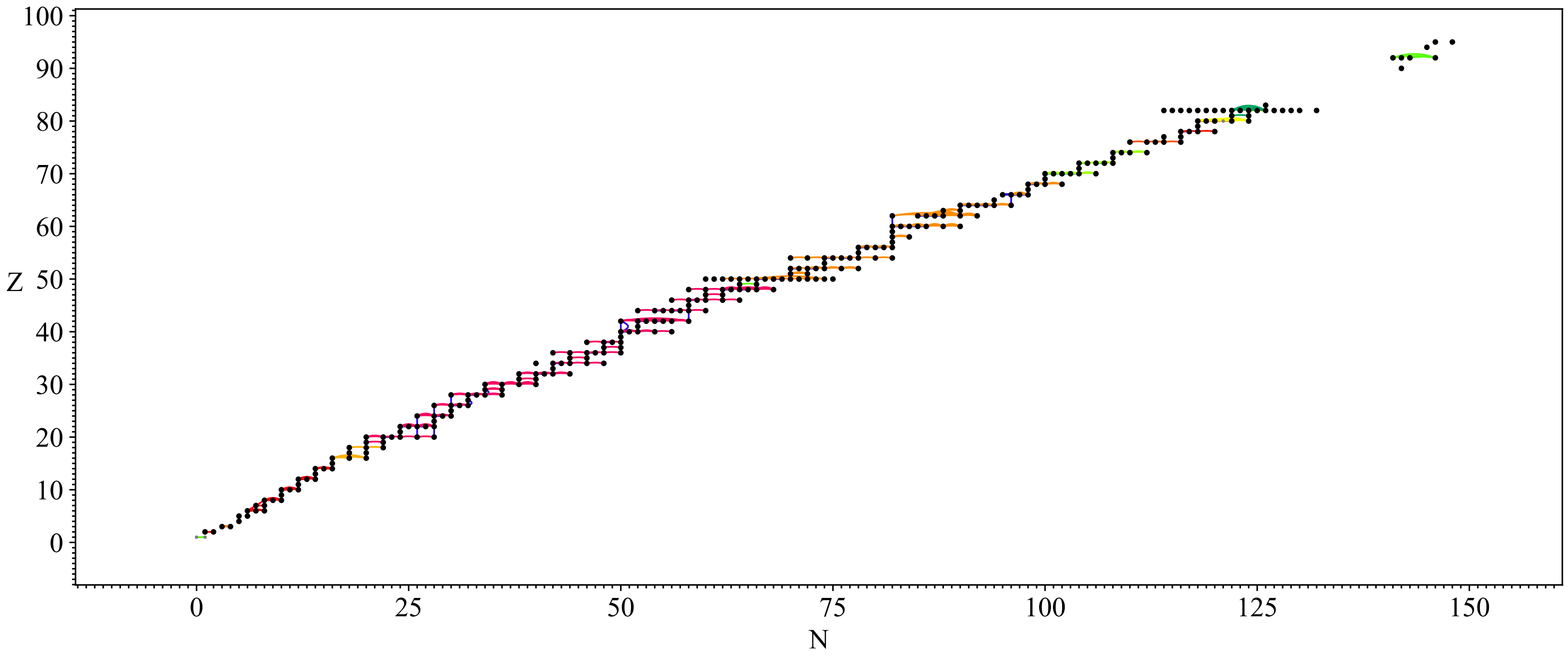
NSF

NIST
National Institute of Standards and Technology

NIST Grant Award Number 70NANB20H87
National Science Foundation Award Number 2309273

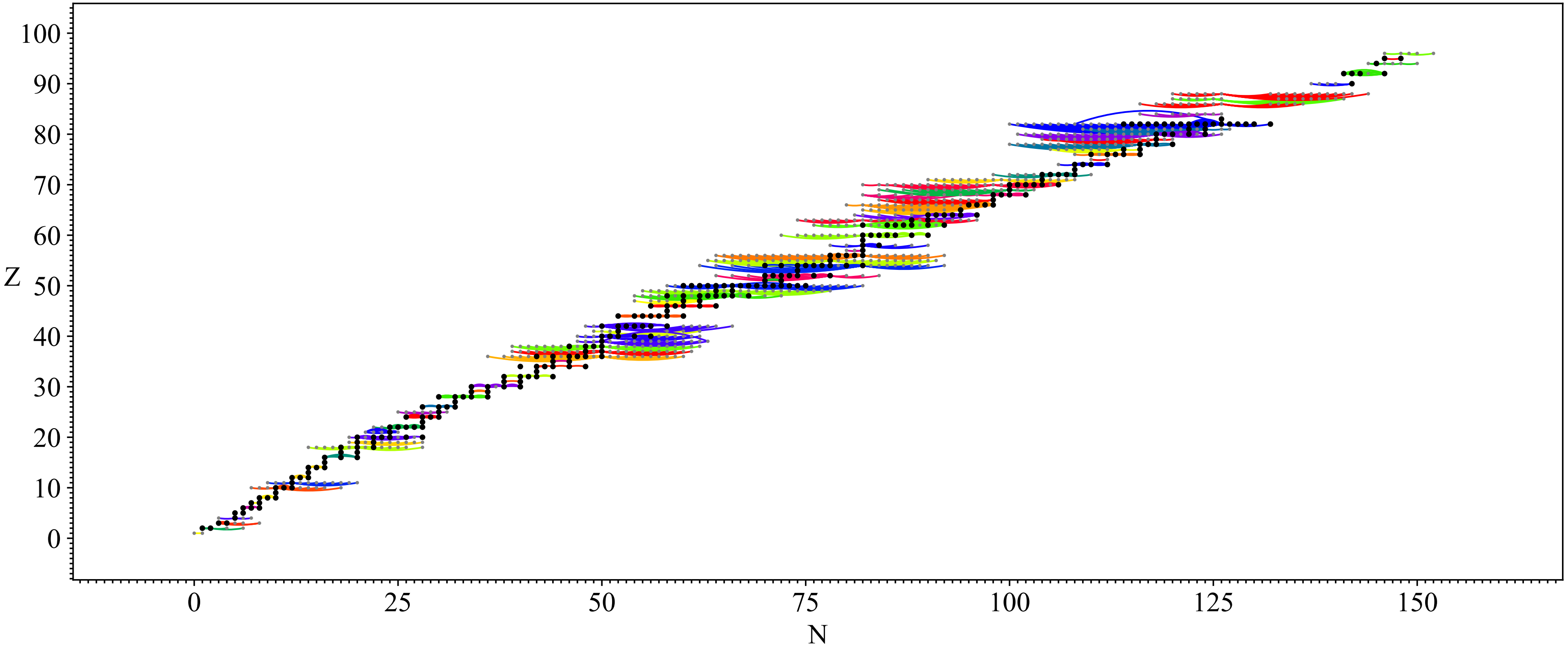
Objective 1: Grouping / Graph Exploration

Users should be able to group data quickly and flexibly!



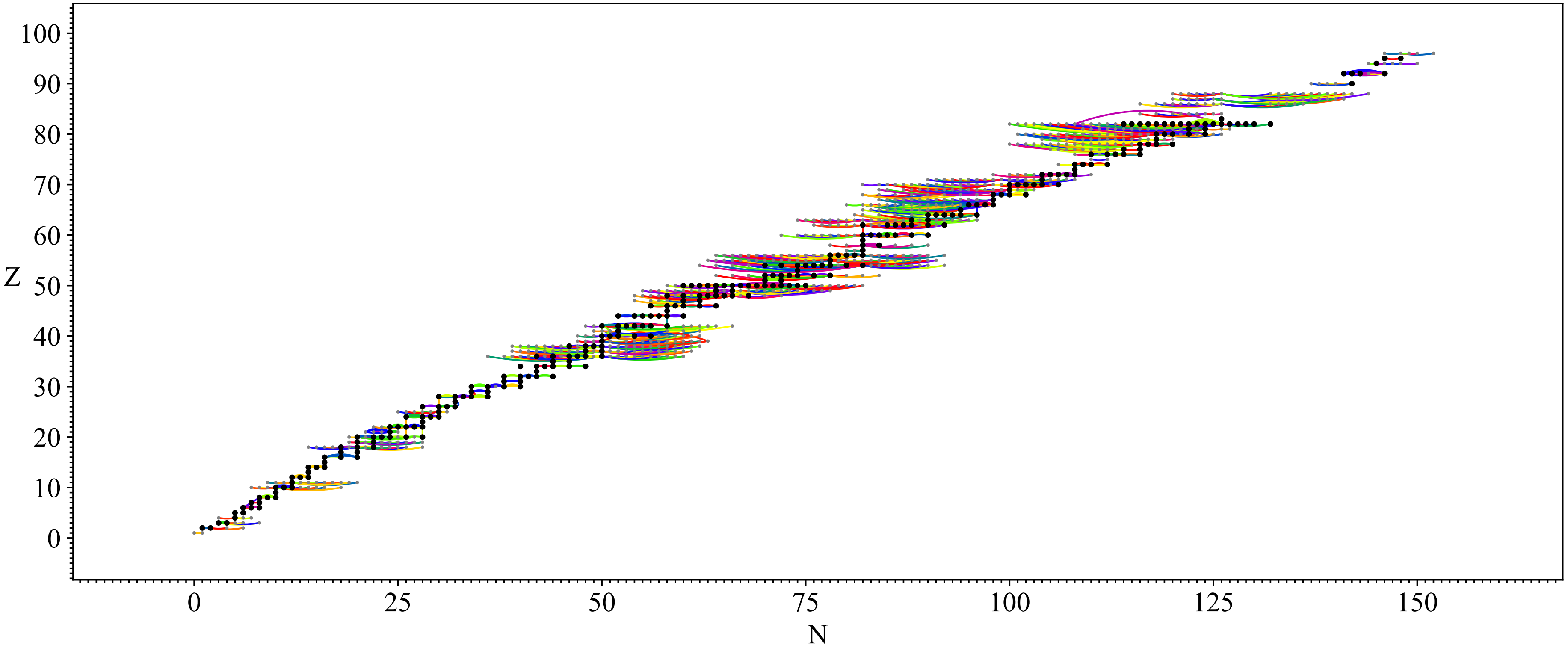
Objective 1: Grouping / Graph Exploration

Whether that be by element:



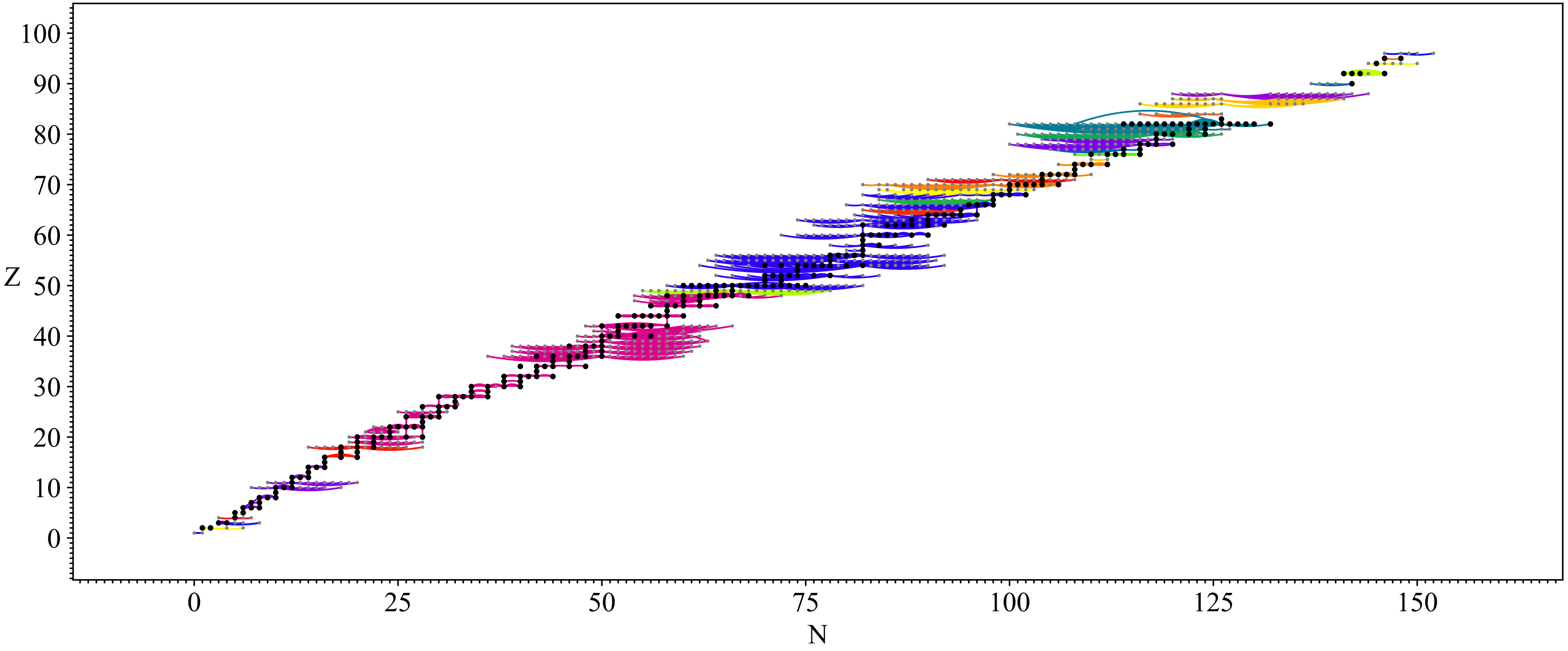
Objective 1: Grouping / Graph Exploration

Or by measured quantity:



Objective 1: Grouping / Graph Exploration

Or by group in the network:



Department of PHYSICS AND ASTRONOMY Clemson® University

Correlation from Conversion: OIS

$$\delta\nu_i^{AA'} = F_i \Lambda^{AA'} + M_i \frac{A-A'}{AA'}$$

Where:

$$\Lambda^{AA'} = \delta\langle r^2\rangle^{AA'} + \frac{C_2}{C_1}\delta\langle r^4\rangle^{AA'} + \frac{C_3}{C_1}\delta\langle r^6\rangle^{AA'}$$

F_i: Transition specific electronic factor
M_i: Transition specific mass factor – includes normal and specific mass shifts
C_i: The Seltzer coefficients

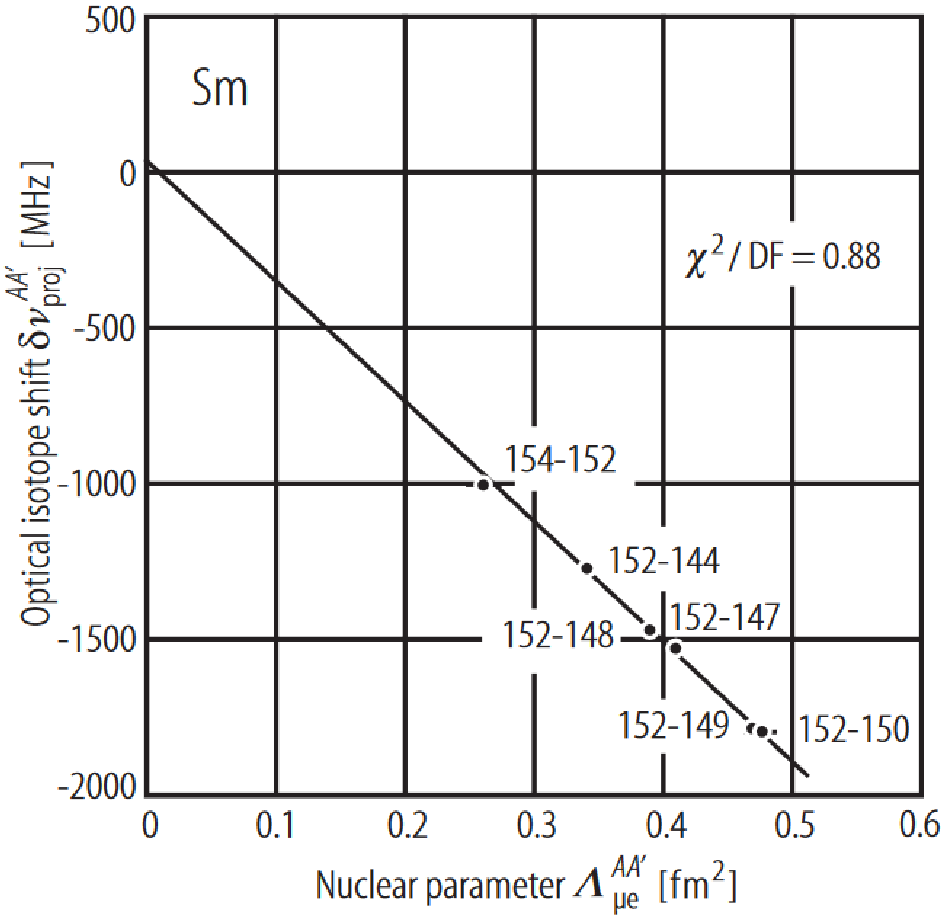
Correlations from Conversion: OIS

$$\delta\left\langle r^2\right\rangle_{1,k}^{e\mu OIS} = \left(\frac{\delta\left\langle r^2\right\rangle_{1,k}}{\delta\left\langle r^2\right\rangle_{1,2}}\right)^{OIS} \times \delta\left\langle r^2\right\rangle_{1,2}^{e\mu}$$

Angeli 2004 / 2013 used a correction factor determined from comparing OIS radii differences to electronic and muonic radii differences.

Correlations from Conversion: OIS

King plot was used in Fricke 2004 – directly fit parameters of OIS equation.



Correlations from Conversion: OIS

Covariance matrix elements:

$$Cov[\delta\langle r^2\rangle^{A^iA'}, \delta\langle r^2\rangle^{A^jA'}] \approx Cov[F\delta\nu^{A^iA'}, \delta\nu^{A^jA'}] =$$

$$\left(\frac{\Delta F}{F}\right)^2 \delta\nu^{A^iA'}\delta\nu^{A^jA'} + \delta_{ij}\left(\frac{\Delta\delta\nu^{A^jA'}}{F}\right)^2$$

Correlations from Conversion: OIS

```
[[ 0.00010000001 -0.0001          -0.0002        ]
 [-0.0001         0.00010000001   0.0002        ]
 [-0.0002         0.0002          0.00040000001]]
```

name	value	standard error	relative error
dR2_19_20	-0.10000000	0.01000000	(10.00%)
dR2_21_20	0.10000000	0.01000000	(10.00%)
dR2_22_20	0.20000000	0.02000000	(10.00%)

Correlations from Conversion: OIS

Standard weighted least-squares, vary F

name	value	standard error	relative error
F	0.10000000	5.0000e-04	(0.50%)
dR2_19_20	-0.10000000	5.0000e-04	(0.50%)
dR2_21_20	0.10000000	5.0000e-04	(0.50%)
dR2_22_20	0.20000000	0.00100000	(0.50%)

Generalized least-squares, all radii are parameters

name	value	standard error	relative error
dR2_19_20	-0.10000000	4.9939e-04	(0.50%)
dR2_21_20	0.10000000	4.9939e-04	(0.50%)
dR2_22_20	0.20000000	9.9875e-04	(0.50%)