Nuclear Radii, V_{ud} and CKM Unitarity

Misha Gorshteyn
Universität Mainz

Collaborators:
Chien-Yeah Seng
Michael Ramsey-Musolf
Michael Gennari
Mehdi Drissi
Petr Navratil
Ben Ohayon
Bijaya Sahoo
Vaibhav Katyal
Arup Chakraborty
John Behr

Review “The Standard Model theory of neutron beta decay” MG, Seng, arXiv:**2307.01145**
Review “Superallowed nuclear beta decays and precision tests of SM” MG, Seng, arXiv:**2311.00044**
“Robust treatment of finite nuclear size reduces CKM unitarity deficit”, MG et al arXiv:**2502.17070**

Outline

Cabibbo unitarity: overconstrained Standard Model fails, saved by BSM

V_{ud} from superallowed nuclear β decays

Status of radiative and nuclear structure corrections

Nuclear finite size effects in δ_C and f

Summary & Outlook

Cabibbo Unitarity:
Status in the Standard Model and Beyond

Status of Cabibbo unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)_{V_{ud}}(4)_{V_{us}}$$

~ 0.95 ~ 0.05 $\sim 10^{-5}$

V_{ud} and V_{us} determinations inconsistent with the SM

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Superallowed nuclear β : $\quad |V_{ud}| = 0.9737\,(3)$

At variance with kaon decays + Cabibbo unitarity

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$K \to \pi \ell \nu$: $|V_{us}| = 0.2233(5)$

Unitarity $\to |V_{ud}| = \sqrt{1 - |V_{us}|^2} = 0.9747(1)$

$\frac{K \to \mu\nu}{\pi \to \mu\nu}$: $|V_{us}/V_{ud}| = 0.2311(5)$

Unitarity $\to |V_{ud}| = [1 + |V_{us}/V_{ud}|^2]^{-1/2} = 0.9743(1)$

PDG $[S = 2.5]$: $|V_{us}| = 0.2243(8)$

Unitarity $\to |V_{ud}| = 0.9745(2)$

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But consistent with the free neutron decay: $|V_{ud}| = 0.9743\,(9)$

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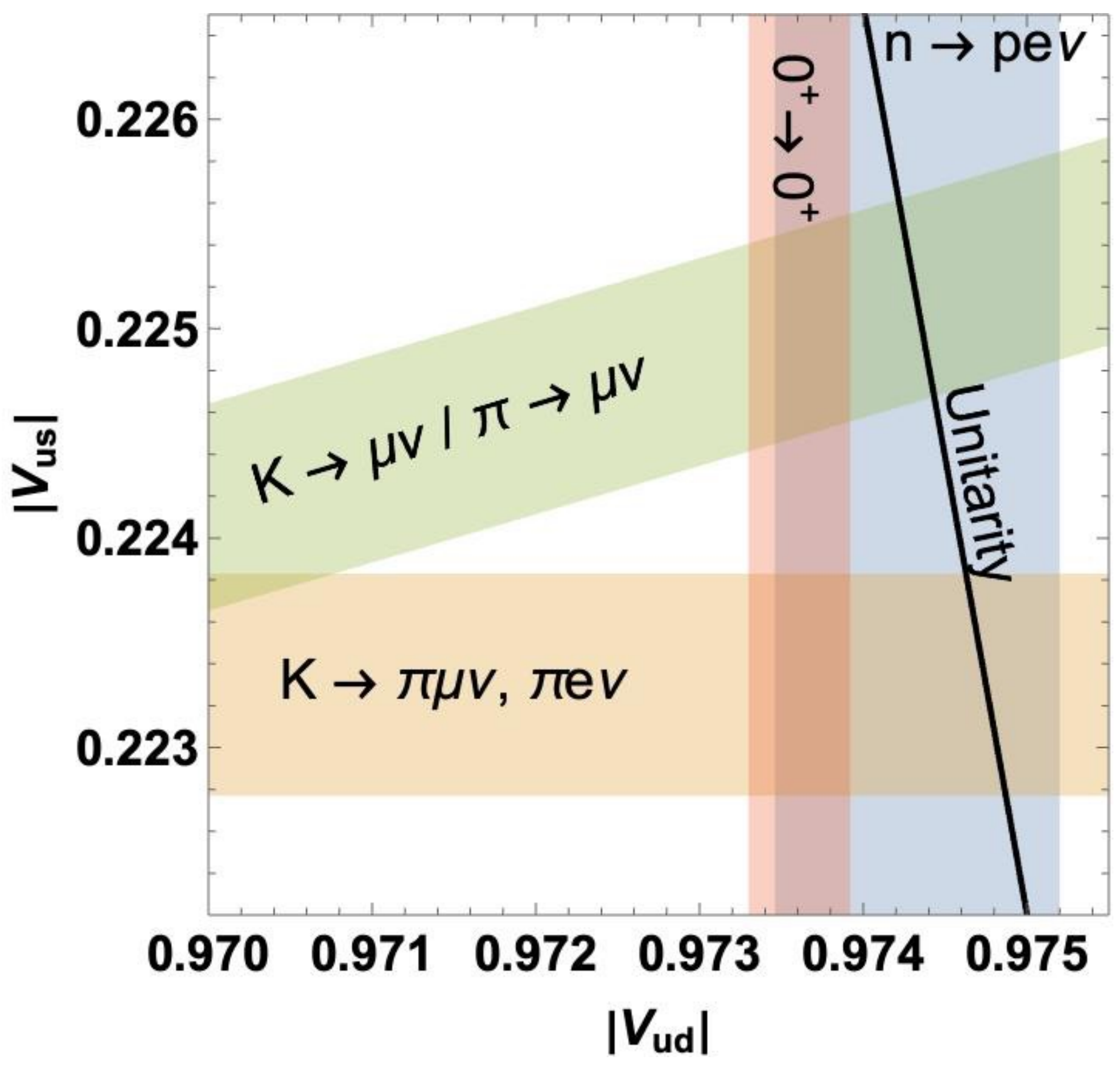
At variance with kaon decays + Cabibbo unitarity



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Cabibbo Unitarity - 3 anomalies!

In SM overconstrained:
3 measurements for 2 unknowns — 3 anomalies

$$\Delta^{(1)}_{\rm CKM} = |V_{ud}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1$$ **= –0.00176(56) –3.1σ**

$$\Delta^{(2)}_{\rm CKM} = |V_{ud}|^2 \left[1 + \left(\left|\frac{V_{us}}{V_{ud}}\right|^{K_{\mu 2}}\right)^2\right] - 1$$ **= –0.00098(58) –1.7σ**

$$\Delta^{(3)}_{\rm CKM} = |V_{us}^{K_{\ell 3}}|^2 \left[\left(\frac{1}{|V_{us}/V_{ud}|^{K_{\mu 2}}}\right)^2 + 1\right] - 1$$ **= –0.0164(63) –2.6σ**

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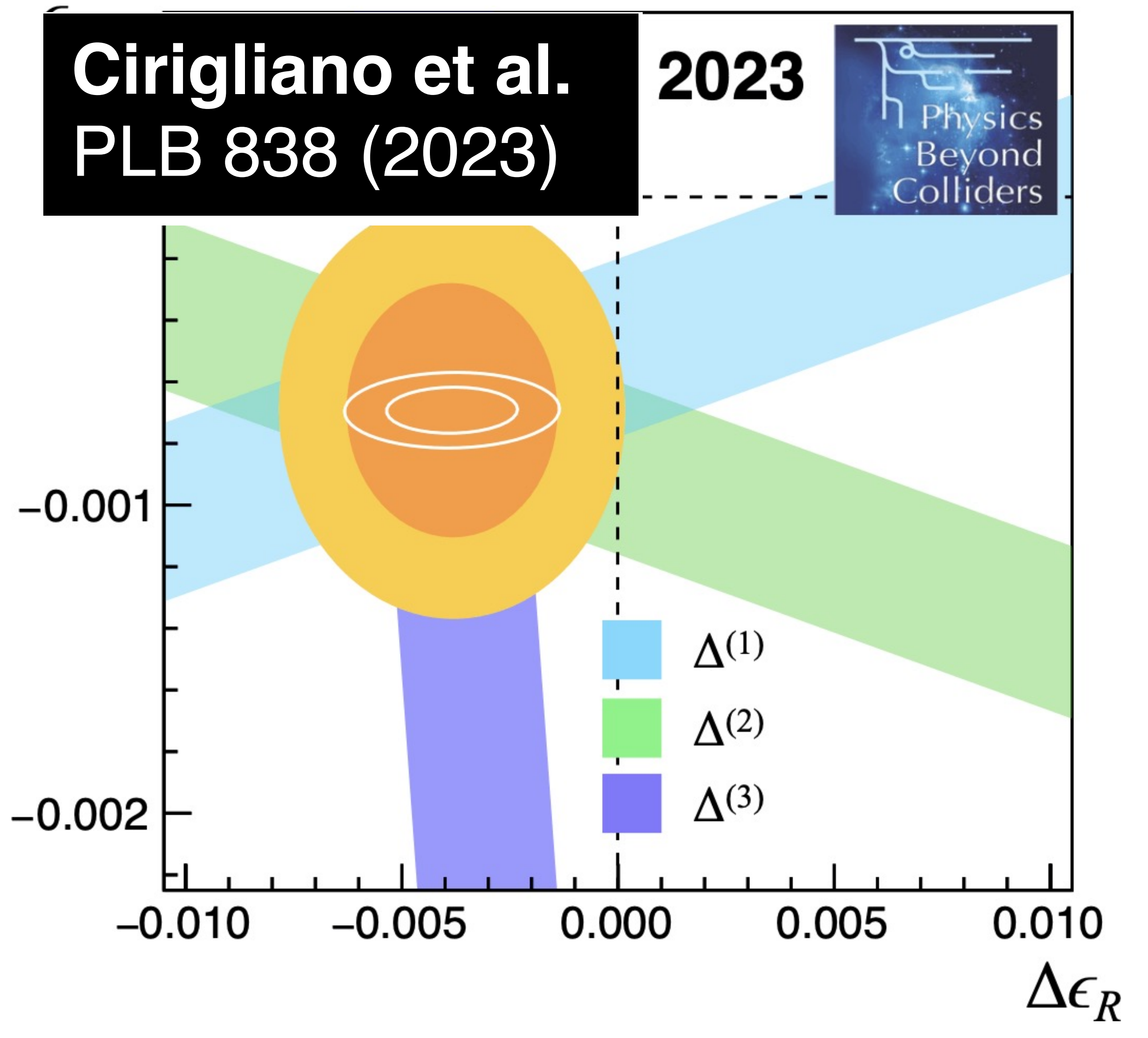
Remove SM overconstraints: Minimal BSM model with RH currents

ϵ_R = admixture of RH currents in non-strange sector
$\epsilon_R + \Delta\epsilon_R$ = admixture of RH currents in strange sector

$$\Delta^{(1)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R V^2_{us}$$
$$\Delta^{(2)}_{\rm CKM} = 2\epsilon_R - 2\Delta\epsilon_R V^2_{us}$$
$$\Delta^{(3)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V^2_{us})$$

From current fit:

$\epsilon_R = -0.69(27) \times 10^{-3}$ (2.5σ)
$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$ (2.4σ)
$\epsilon_R = \Delta\epsilon_R = 0$ excluded at 3.1σ

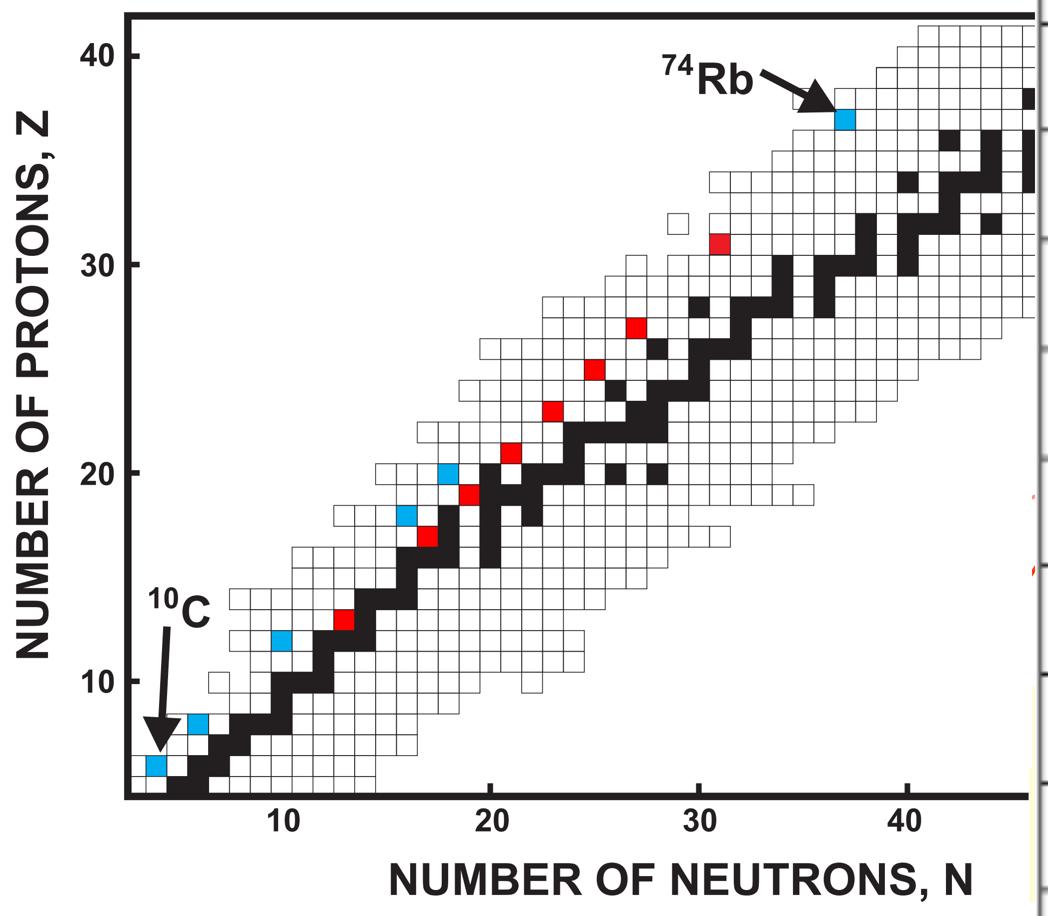


Review the "σ" : Experiment + SM corrections

V_{ud} from superallowed nuclear β decays

V_{ud} from superallowed $0^+ - 0^+$ nuclear decays

1. Transitions within $J^P=0^+$ isotriplets (T=1)
2. Elementary process: p—>ne$^+\nu$
3. Only conserved vector current
4. SU(2) good —> corrections ~small
5. 15 measured to better than 0.2%
6. **Maximally overconstrained: 15/1**



${}^{10}_{6}\mathrm{C} \to {}^{10}_{5}\mathrm{B}$	${}^{26m}_{13}\mathrm{Al} \to {}^{26}_{12}\mathrm{Mg}$
${}^{14}_{8}\mathrm{O} \to {}^{14}_{7}\mathrm{N}$	${}^{34}_{17}\mathrm{Cl} \to {}^{34}_{16}\mathrm{S}$
${}^{18}_{10}\mathrm{Ne} \to {}^{18}_{9}\mathrm{F}$	${}^{38m}_{19}\mathrm{K} \to {}^{38}_{18}\mathrm{Ar}$
${}^{22}_{12}\mathrm{Mg} \to {}^{22}_{11}\mathrm{Na}$	${}^{42}_{21}\mathrm{Sc} \to {}^{42}_{20}\mathrm{Ca}$
${}^{26}_{14}\mathrm{Si} \to {}^{26}_{13}\mathrm{Al}$	${}^{46}_{23}\mathrm{V} \to {}^{46}_{22}\mathrm{Ti}$
${}^{30}_{16}\mathrm{S} \to {}^{30}_{15}\mathrm{P}$	${}^{50}_{25}\mathrm{Mn} \to {}^{50}_{24}\mathrm{Cr}$
${}^{34}_{18}\mathrm{Ar} \to {}^{34}_{17}\mathrm{Cl}$	${}^{54}_{27}\mathrm{Co} \to {}^{54}_{26}\mathrm{Fe}$
${}^{38}_{20}\mathrm{Ca} \to {}^{38}_{19}\mathrm{K}$	${}^{62}_{31}\mathrm{Ga} \to {}^{62}_{30}\mathrm{Zn}$
${}^{42}_{22}\mathrm{Ti} \to {}^{42}_{21}\mathrm{Sc}$	${}^{66}_{33}\mathrm{As} \to {}^{66}_{32}\mathrm{Ge}$
${}^{46}_{24}\mathrm{Cr} \to {}^{46}_{23}\mathrm{V}$	${}^{70}_{35}\mathrm{Br} \to {}^{70}_{34}\mathrm{Se}$
${}^{50}_{26}\mathrm{Fe} \to {}^{50}_{25}\mathrm{Mn}$	${}^{74}_{37}\mathrm{Rb} \to {}^{74}_{36}\mathrm{Kr}$
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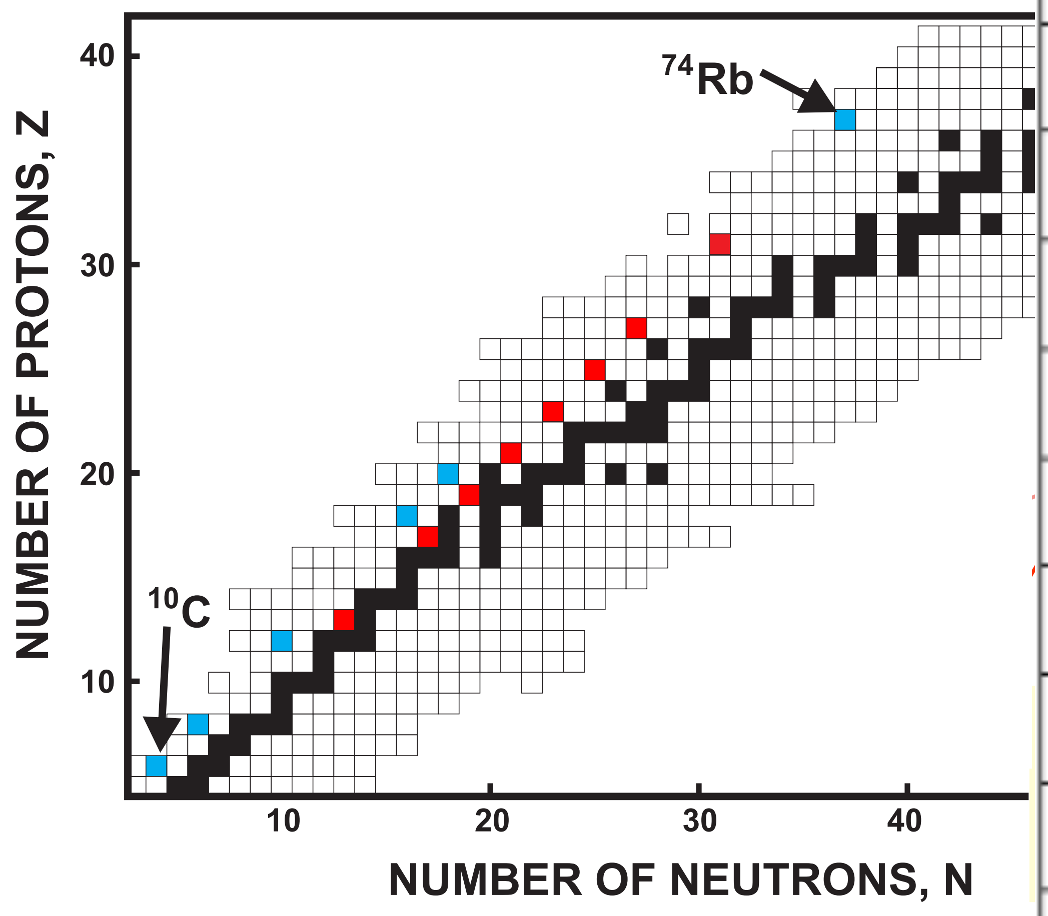

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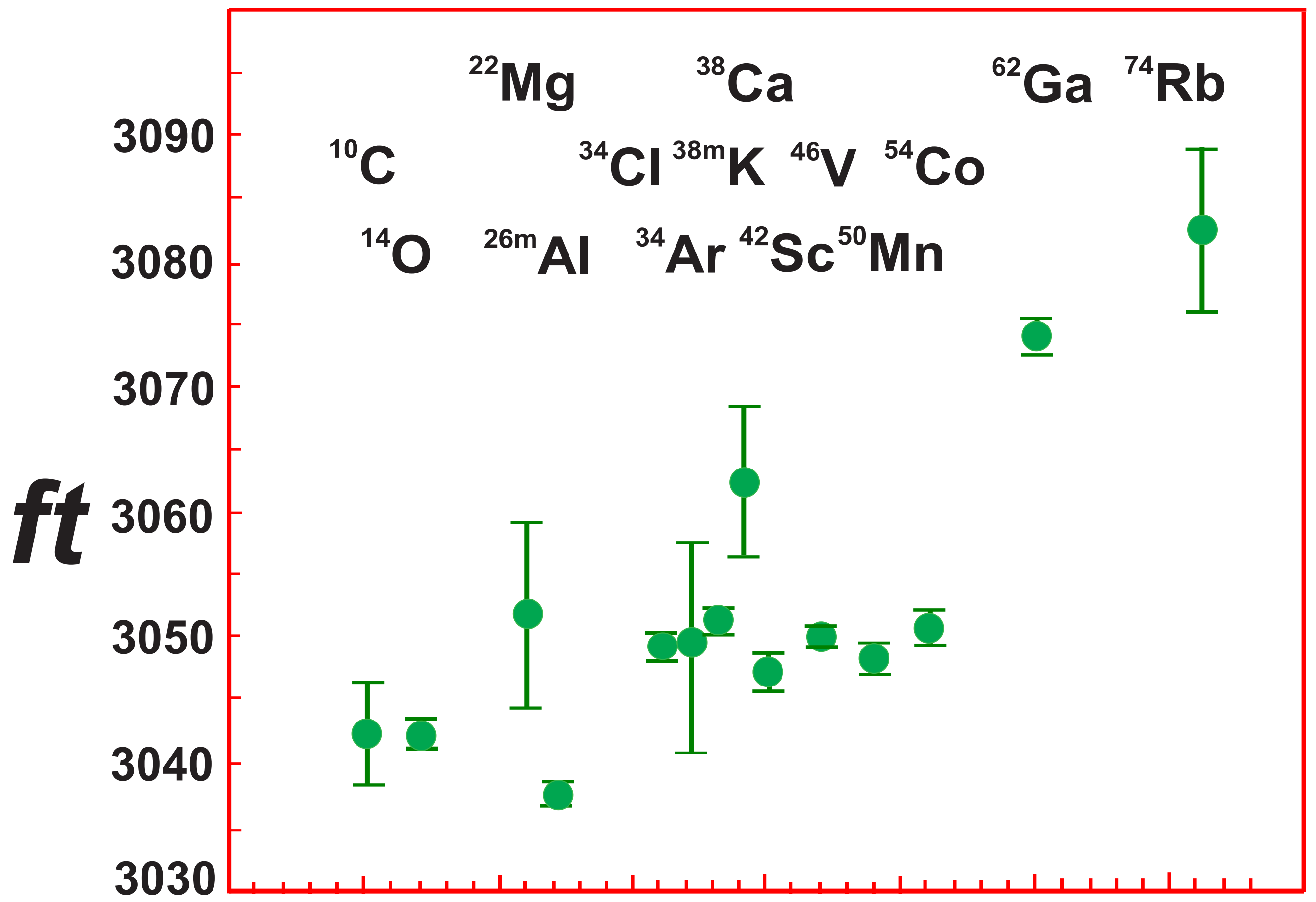
Exp.: **f** - phase space (Q value)

t - partial half-life ($t_{1/2}$, branching ratio)



ft values: same within ~2% but not exactly!

Reason: SU(2) slightly broken

a. RC (e.m. interaction does not conserve isospin)
b. Nuclear WF are not SU(2) symmetric
   (proton and neutron distribution not the same)

V_{ud} extraction: Universal RC and Universal Ft

To obtain Vud —> absorb all decay-specific corrections into universal **Ft**

$$ft(1 + \mathrm{RC} + \mathrm{ISB}) = \mathscr{F}\mathrm{t}(1 + \Delta_\mathrm{R}^\mathrm{V}) = \mathrm{ft}(1 + \delta_\mathrm{R}')(1 - \delta_\mathrm{C} + \delta_\mathrm{NS})(1 + \Delta_\mathrm{R}^\mathrm{V})$$

~ Measured   QED   Isospin-breaking   Nuclear structure   Universal RC

$$|V_{ud}|^2 = \frac{2984.43s}{\mathscr{F}t(1 + \Delta_R^V)}$$

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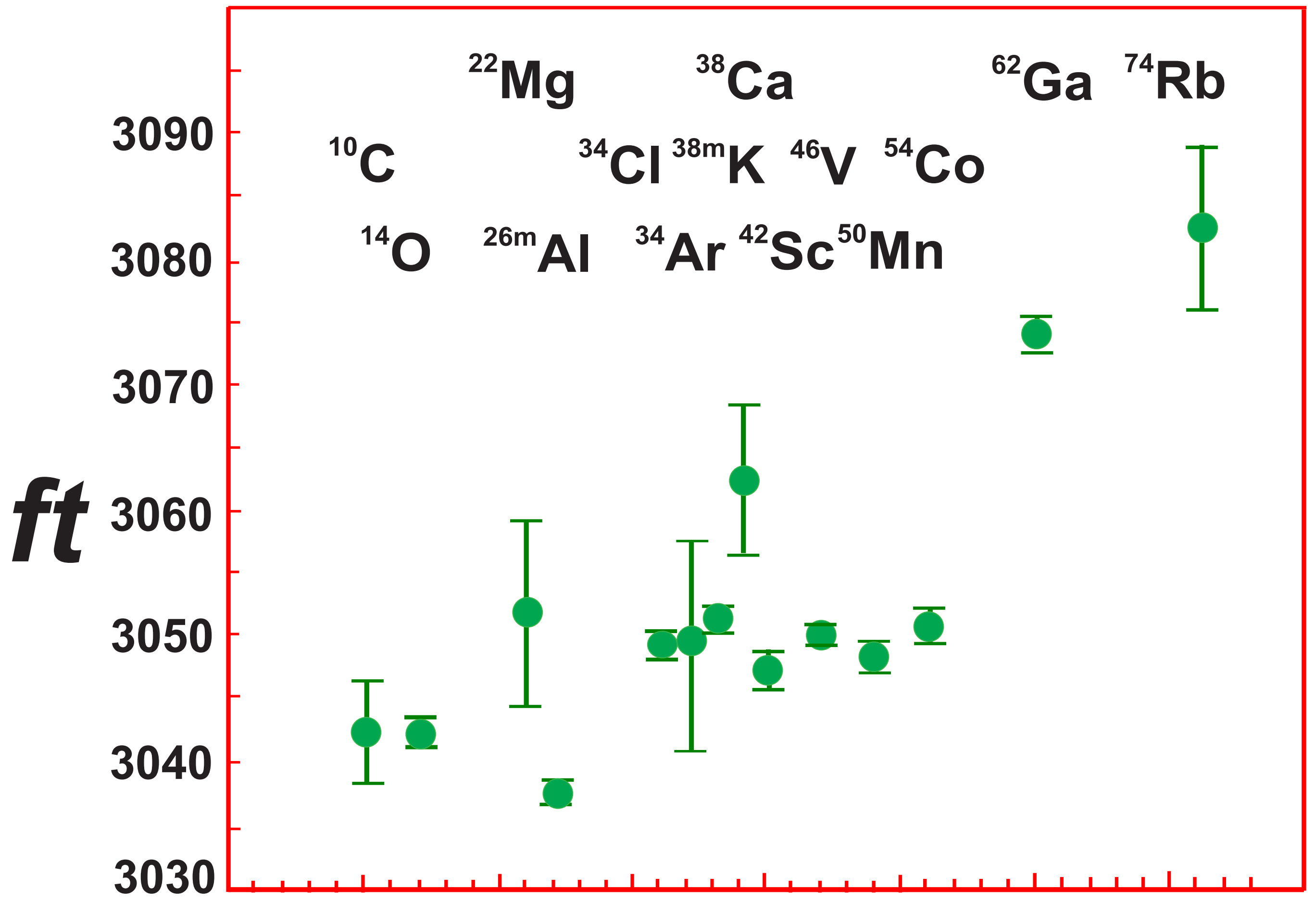
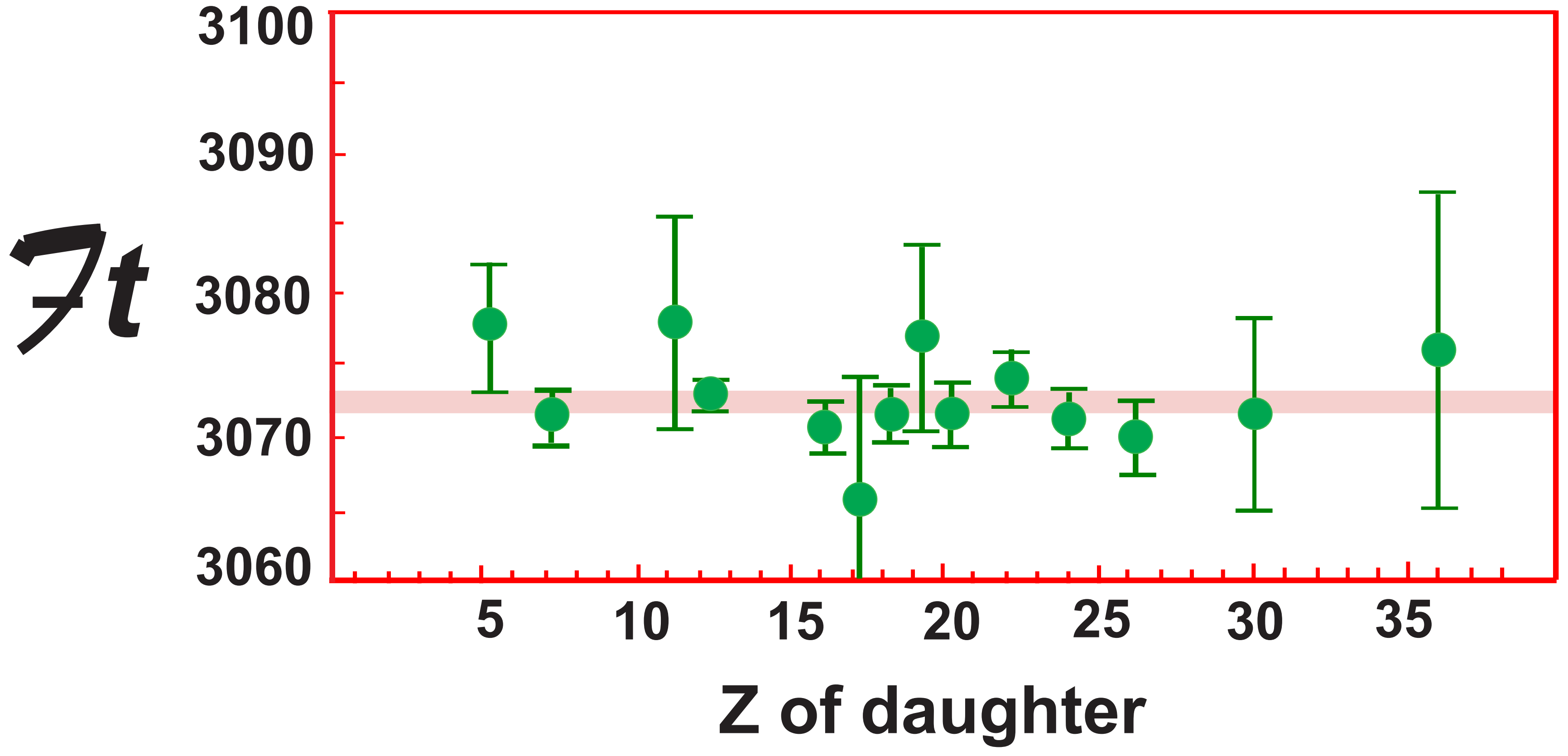


Average of 15 decays

Hardy, Towner 1972 - 2020

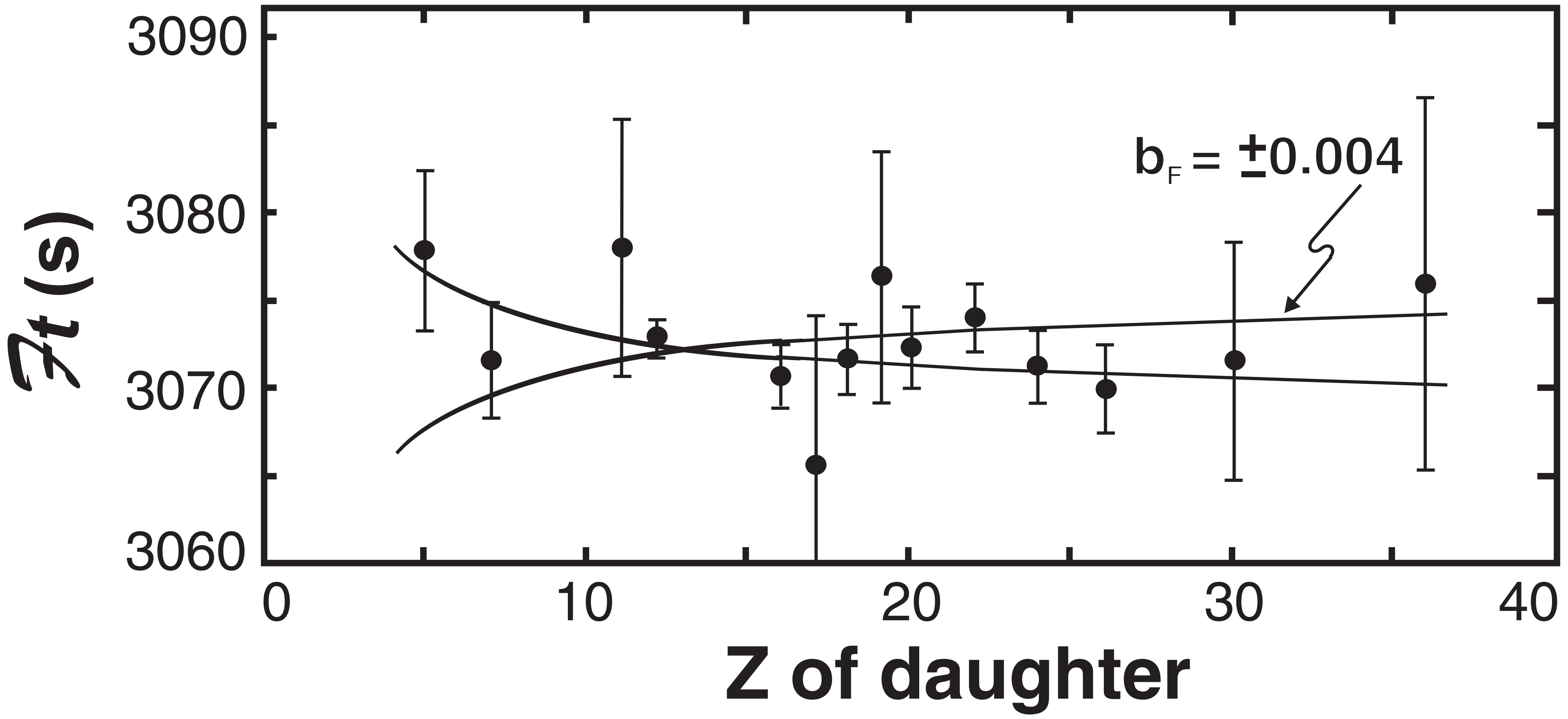
Pre-2018: $\overline{\mathscr{F}t} = 3072.1 \pm 0.7\, s$

PDG 2024: $\overline{\mathscr{F}t} = 3072 \pm 2\, s$



$$|V_{ud}^{0^+-0^+}| = 0.9737\,(1)_{exp}\,(3)_{NS}\,(1)_{RC}[3]_{total}$$

BSM searches with superallowed beta decays



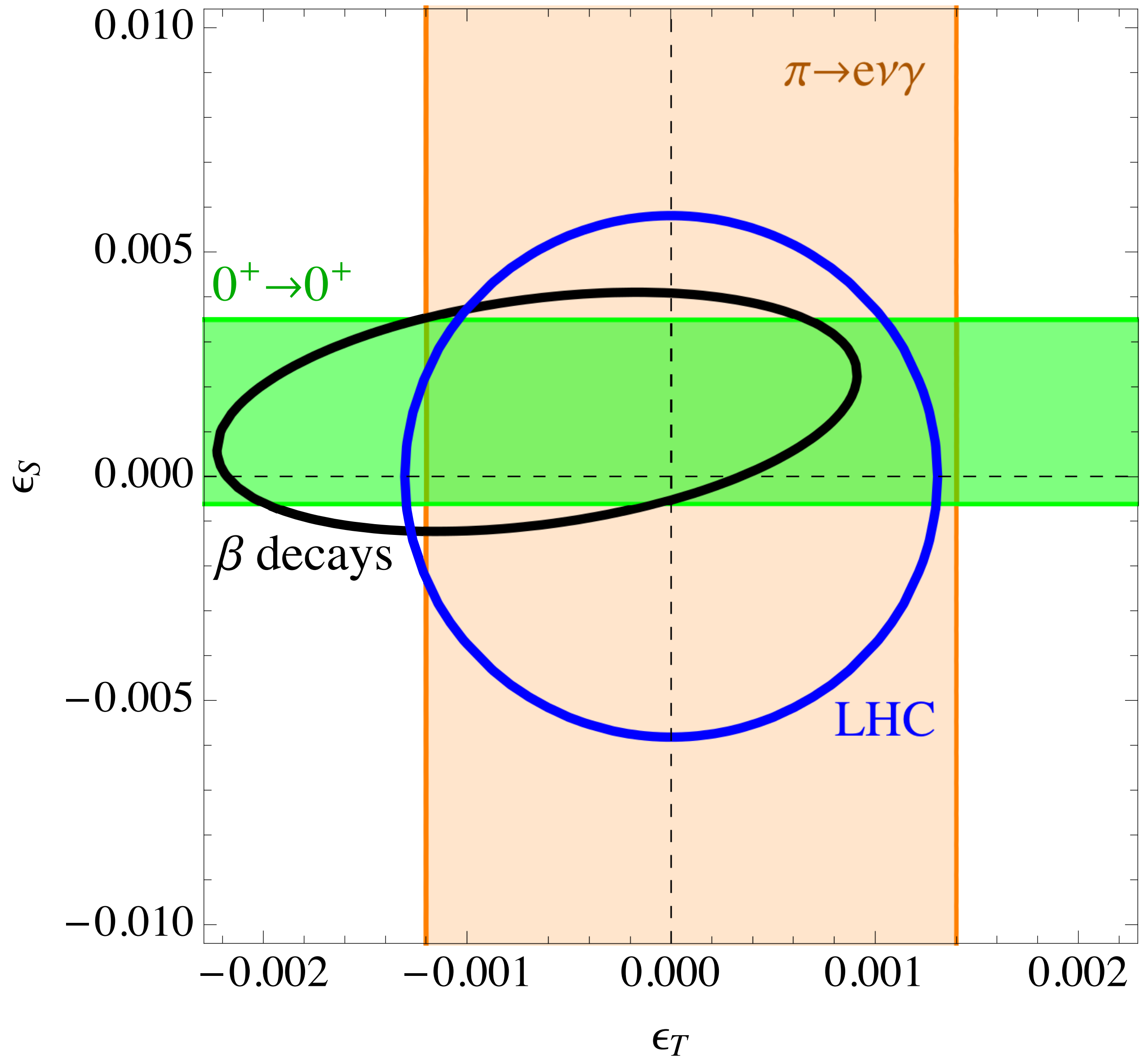
Superallowed decays are quite restrictive to BSM, too!
Only scalar CC (Fierz interference bF) possible

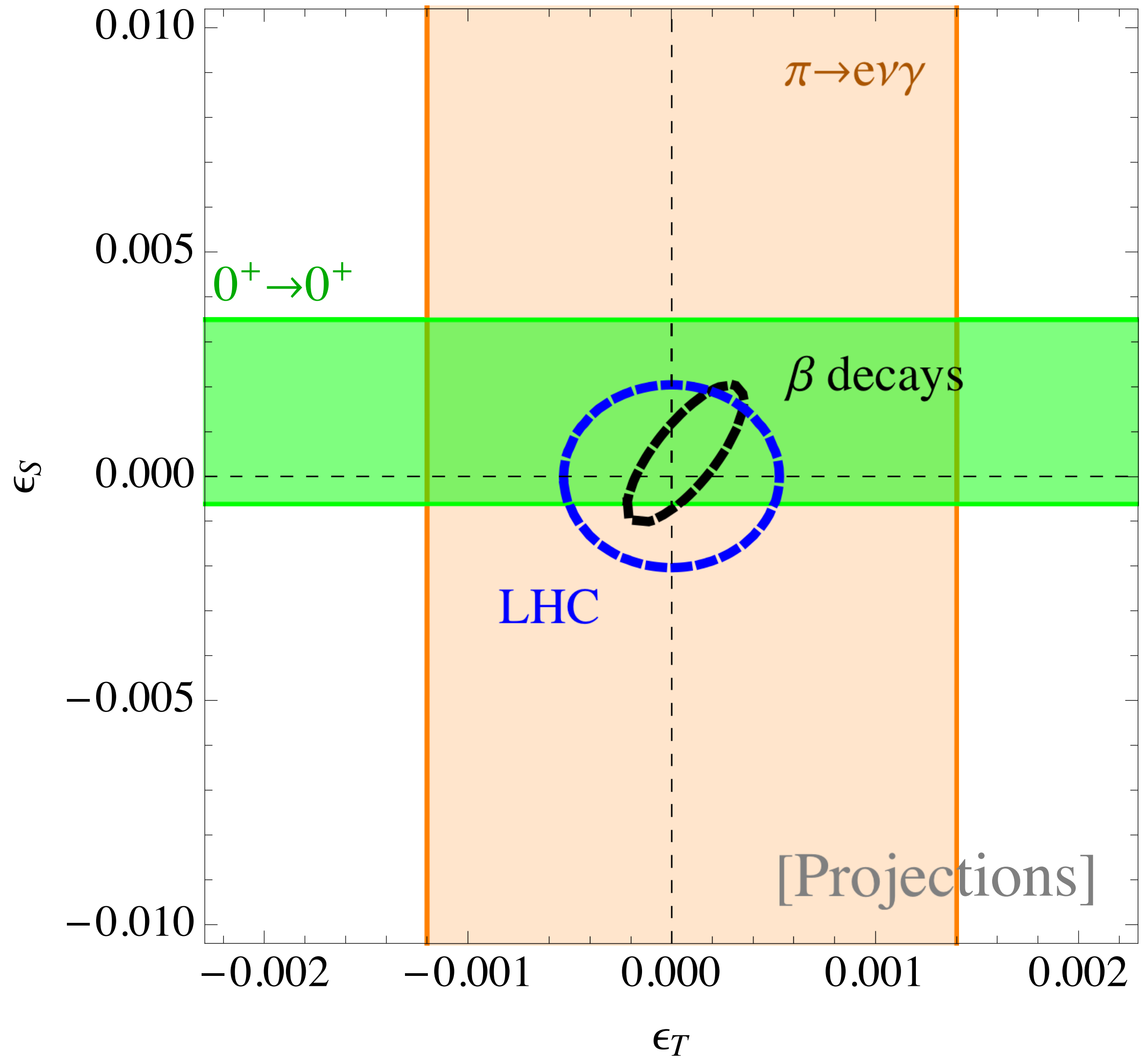
$$\mathscr{F}t^{SM} \rightarrow \mathscr{F}t^{SM}\left(1 + b_F \frac{m_e}{\langle E_e \rangle}\right) \qquad b_F = -0.0028(26)$$

Stringent test of SM and BSM independent of V_{us} and CKM unitarity

Beta decay vs. LHC on Scalar/Tensor CC
Complementarity now and in the future!

Gonzalez-Alonso et al 1803.08732





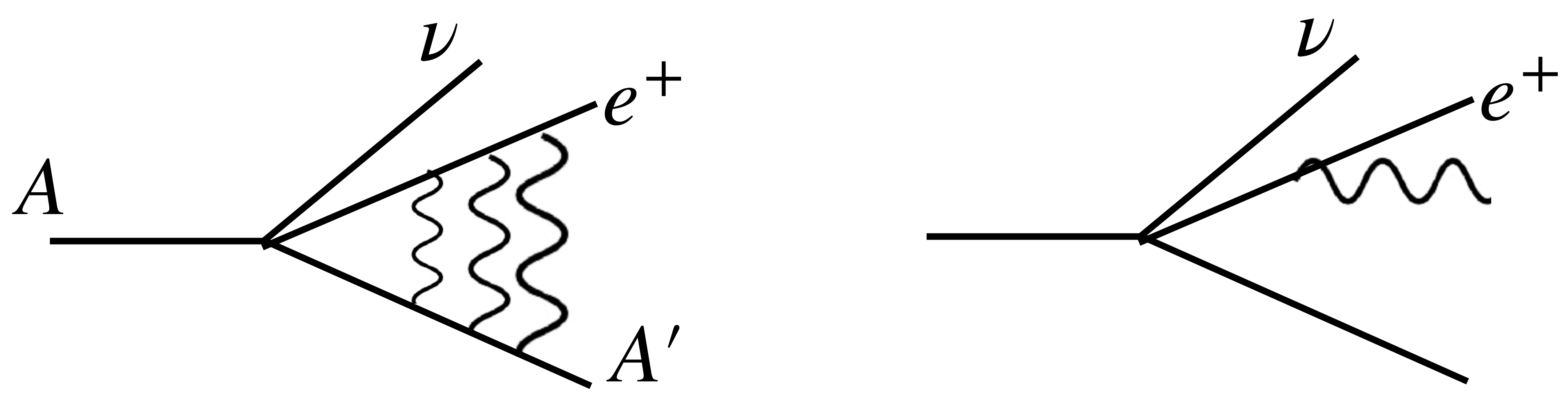
SM Radiative Corrections:

Status of universal RC Δ_R^V

Status of nuclear structure correction δ_{NS}

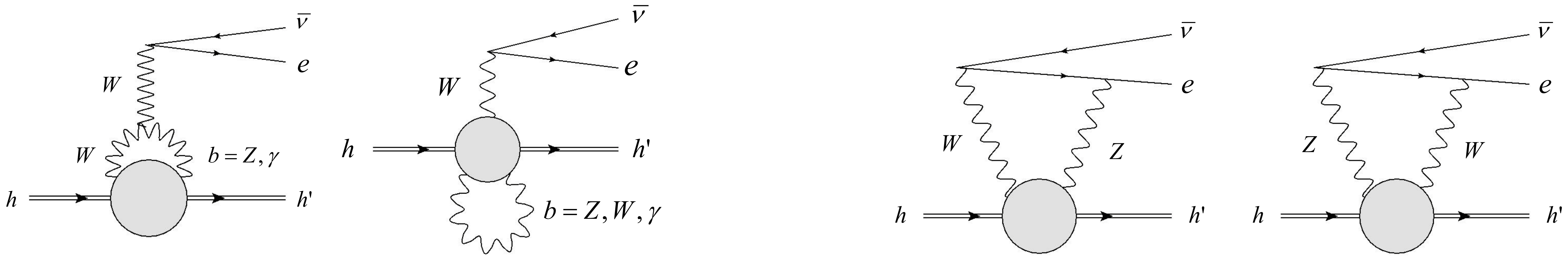
Radiative Corrections to beta decay: sensitivity to scales from IR to UV

IR: Fermi function (Dirac-Coulomb problem)
+ **Sirlin function** (soft Bremsstrahlung)



UV: large EW logs + pQCD corrections

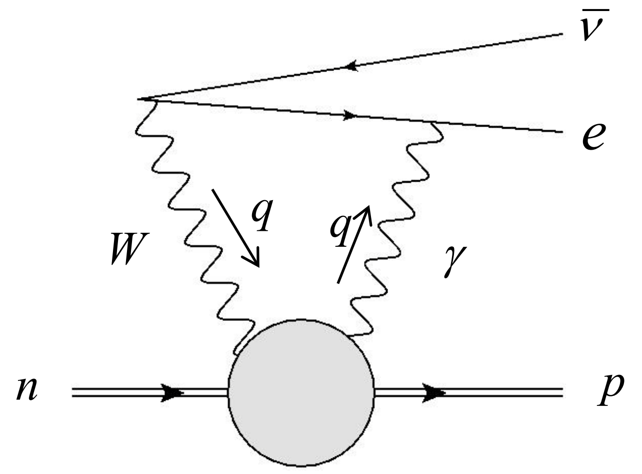
Inner RC:
energy- and model-independent



γW-box: sensitive to all scales

UV-sensitive γW-box on free neutron Δ_R^V: Sirlin, Marciano, Czarnecki 1967 - 2006

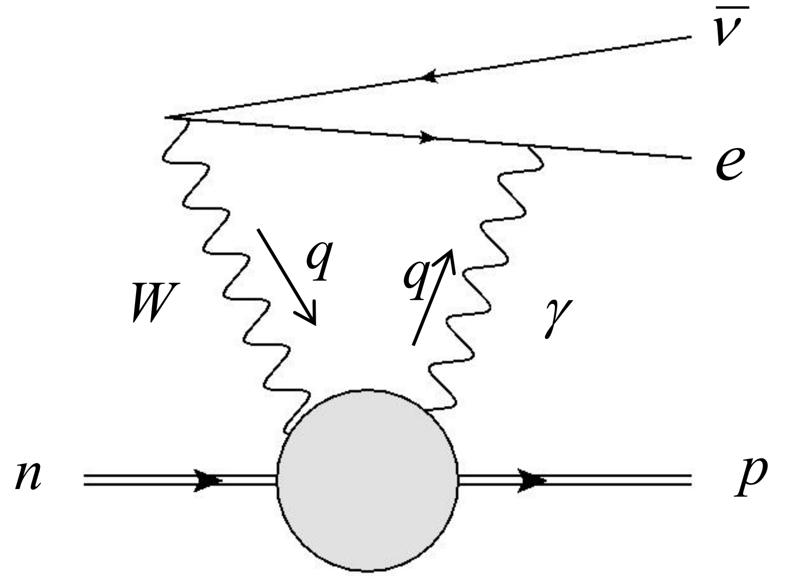
$$\Delta_R^V = \frac{\alpha}{2\pi}\left\{3\ln\frac{M_Z}{M_p} + \ln\frac{M_Z}{M_W} + \tilde{a}_g\right\} + \delta_{\rm QED}^{HO} + 2\,\Box_{\gamma W}$$



All non-enhanced terms $\sim \alpha/2\pi \sim 10^{-3}$ — only need to ~10% — quite doable!

Status of Δ_R^V

2018: reevaluation of **non-enhanced** terms (γW-box) with new methods



Dispersion Theory + neutrino data: $\Delta_R^V = 0.02467(22)$ **Seng, MG, Ramsey-Musolf, 1807.10197; 1812.03352**

Confirmed by lattice QCD:
LQCD on pion + pheno: $\Delta_R^V = 0.02477(24)_{\mathrm{LQCD}^{\pi}+\mathrm{pheno}}$ **Seng, MG, Feng, Jin, 2003.11264** **Yoo et all, 2305.03198**

LQCD on neutron: $\Delta_R^V = 0.02439(19)_{\mathrm{LQCD}^{n}}$ **Ma, Feng, MG et al 2308.16755**

Compare to the previous evaluation: $\Delta_R^V = 0.02361(38)$ **Marciano, Sirlin hep-ph/0510099**

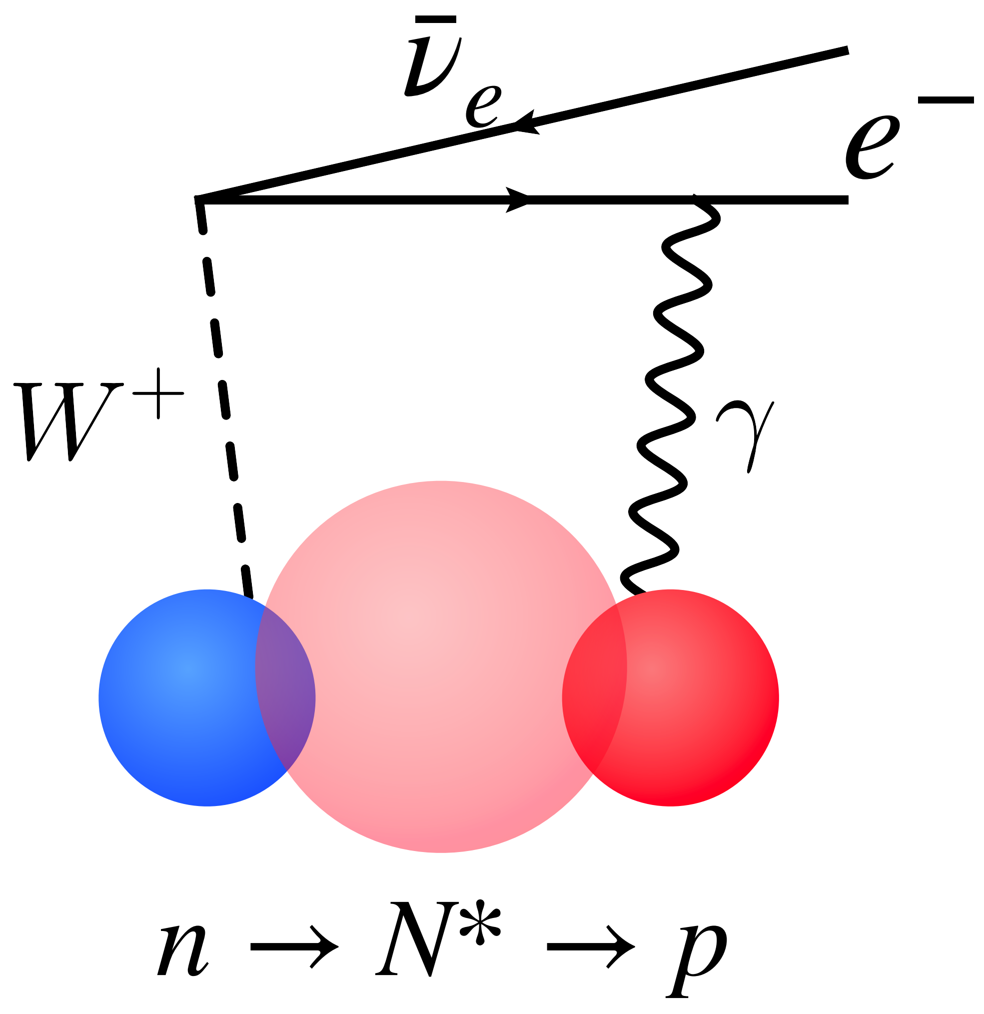
Shift upwards by 3σ + reduction of uncertainty by factor 2 — origin of Cabibbo anomaly

δ_{NS} : the low-energy part of γW-box

Convention: extract free-nucleon γW box

$$\mathscr{F}t(1+\Delta_R^V) = ft(1+\delta_R')(1-\delta_C+\delta_{\rm NS})(1+\Delta_R^V)$$

$$\Delta_R^V \propto 2\,\Box_{\gamma W}^{\rm VA,\,free\,n}$$



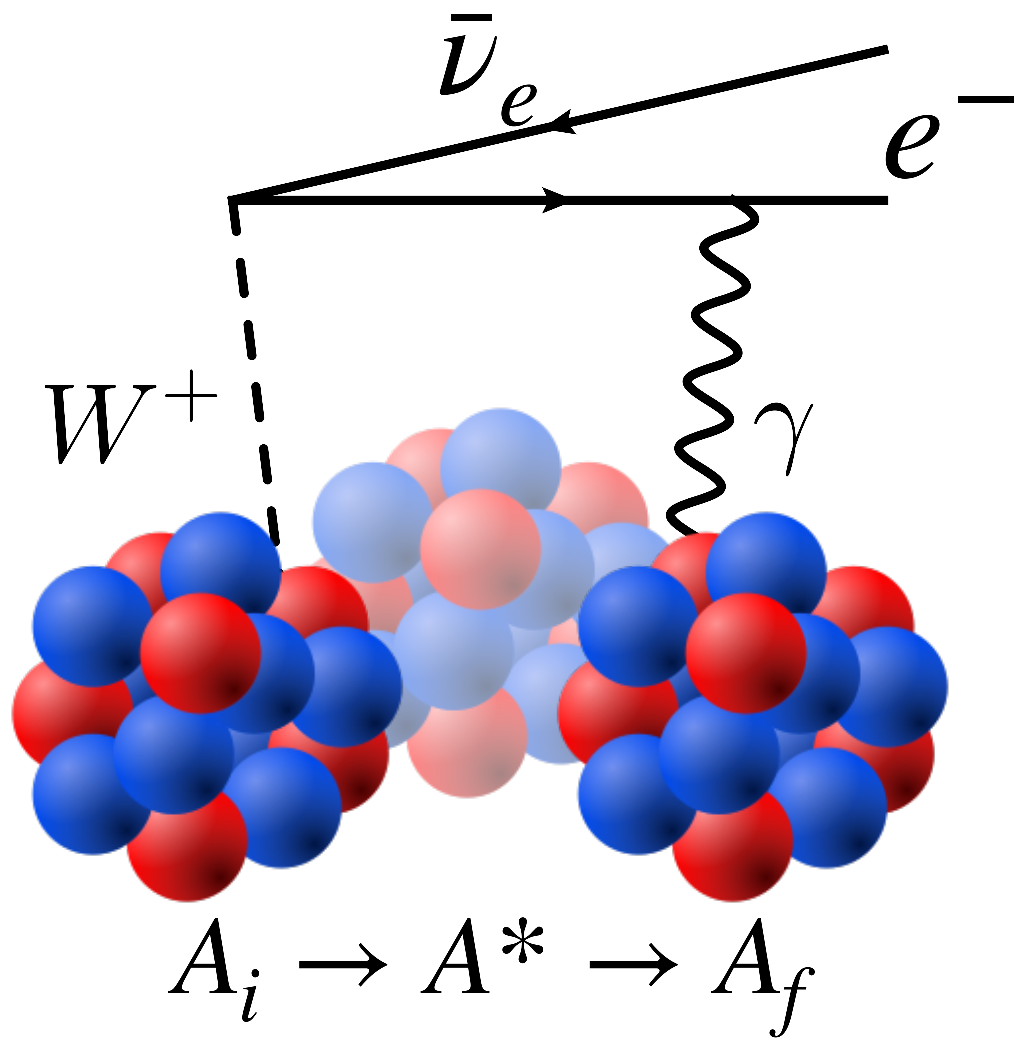
Differences due to:

Richer excitation spectrum in nuclei

Different quantum numbers

$$\delta_{\rm NS} = 2[\,\Box_{\gamma W}^{\rm VA,\,nucl} - \Box_{\gamma W}^{\rm VA,\,free\,n}\,]$$

$$\Delta_R^V + \delta_{\rm NS} \propto 2\,\Box_{\gamma W}^{\rm VA,\,nucl}$$



Separation nucleus — free nucleon controlled in dispersion theory

Evaluate the LE part with appropriate methods: ab initio nuclear theory

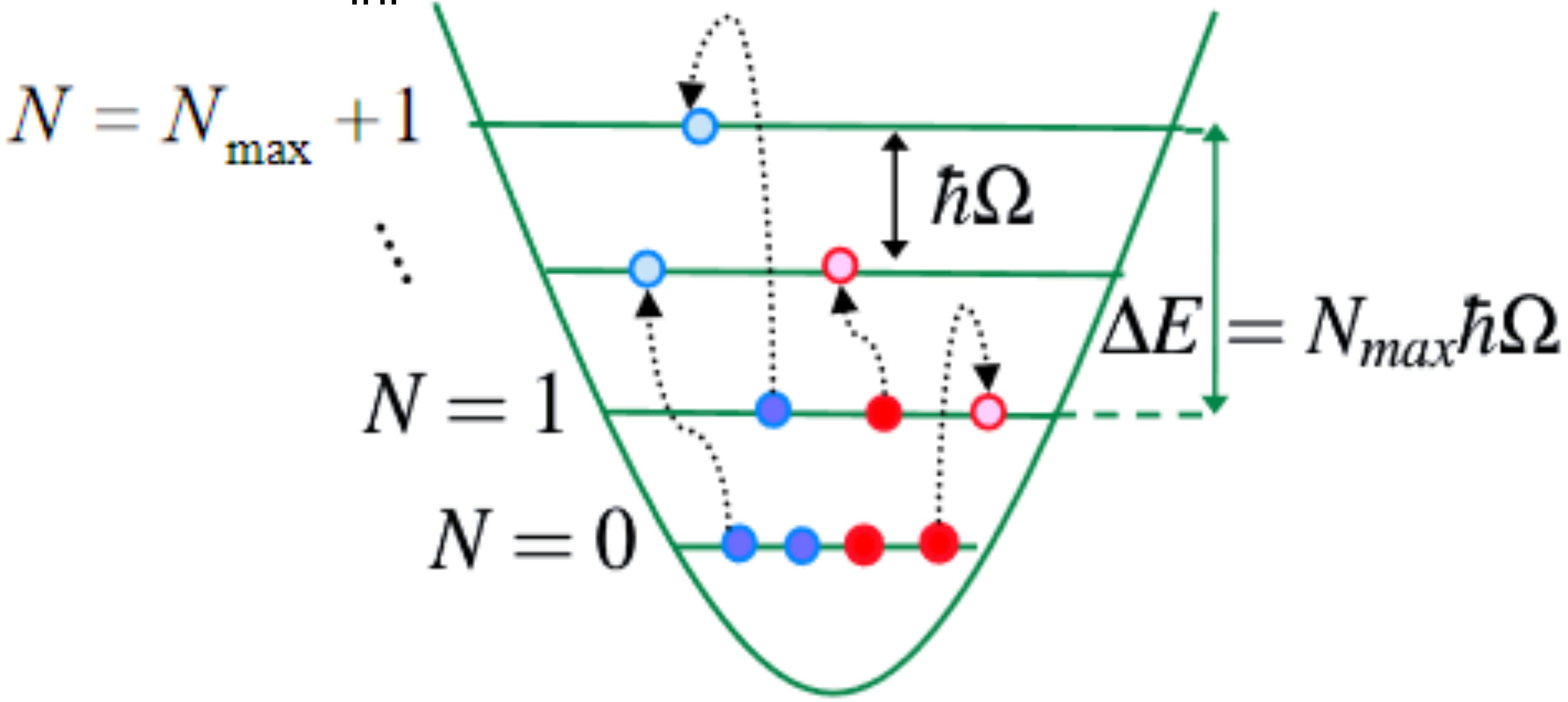
δ_{NS} in ab-initio nuclear theory

First case study: $^{10}C \to {}^{10}B$ in No-Core Shell Model (NCSM)

Many-body problem in HO basis with separation Ω and up to $N = N_{max} + N_{Pauli}$

- Nuclear interactions from Chiral EFT:
  - NN-N^4LO+$3N_{lnl}$
  - NN-N^4LO+$3N^*_{lnl}$

Entem, Machleidt and Nosyk, 2017 PRC;
Gysbers et al., 2019 Nature;
Kravvaris, Navrátil, Quaglioni, Hebborn and Hupin, 2023 PLB



Evaluate the m.e. of nuclear Green's function

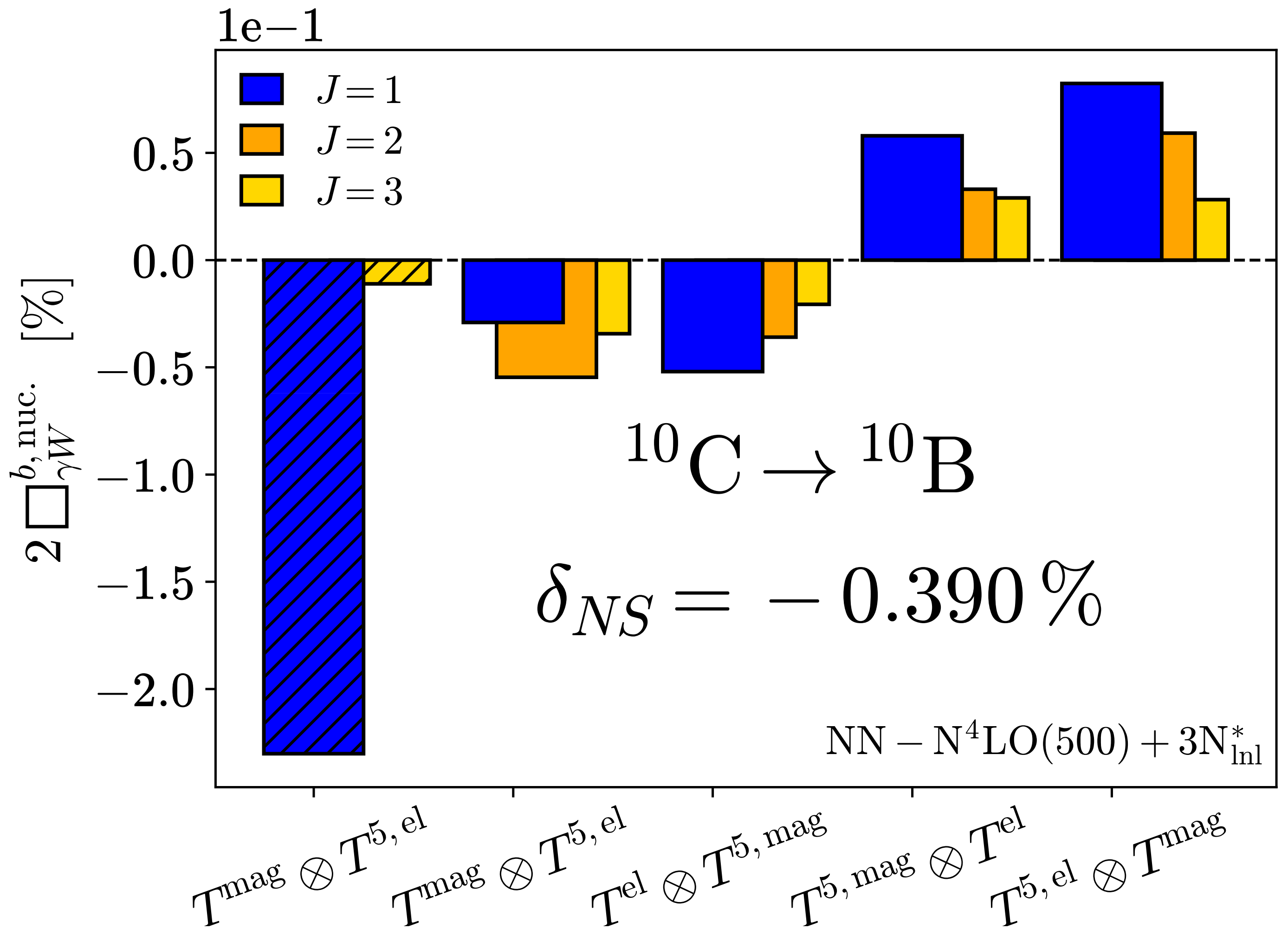
$$G(z) \equiv \frac{1}{z - H_0}$$

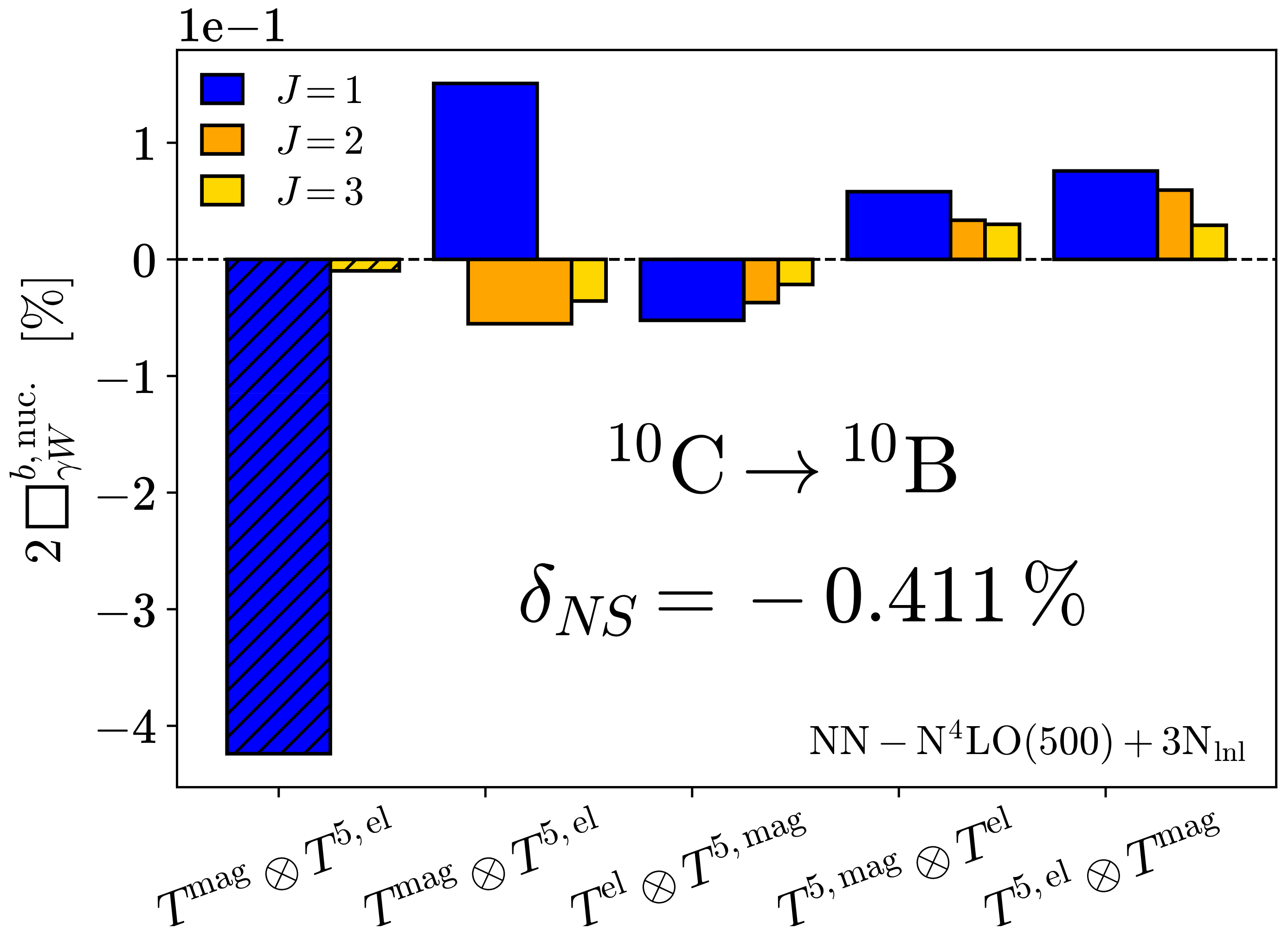
Difficulty: Inverting a large matrix!

Lanczos continuous fraction method

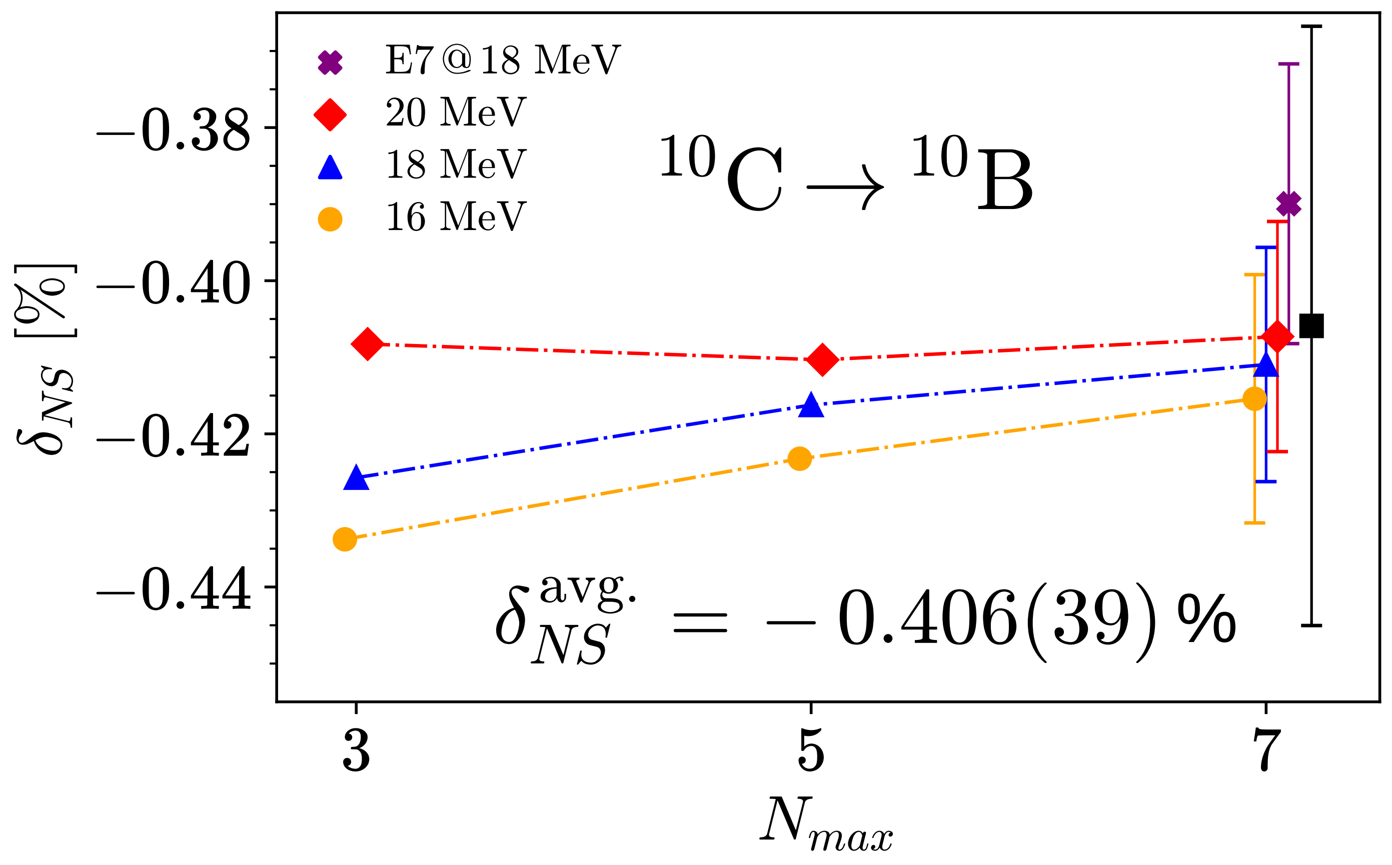
Gennari, Drissi, MG, Navratil, Seng 2405.19281

Ab-initio δ_{NS} for $^{10}C \to {}^{10}B$ transition in NCSM





Check **Ω-independence** and **convergence w.r.t. N_{max}**



No-Core Shell Model (NCSM) $\delta_{NS} = -0.406(39)\,\%$ **Gennari, Drissi, MG, Navratil, Seng 2405.19281**

Compare to Hardy-Towner (old-fashion SM)

$\delta_{NS} = -0.347(35)\,\%$ (2014) Dispersion formalism: correct account for quasielastic knockout and energy dependence $\delta_{NS} = -0.400(50)\,\%$ (2020)

Seng, MG, Ramsey-Musolf, 1812.03352; MG 1812.04229

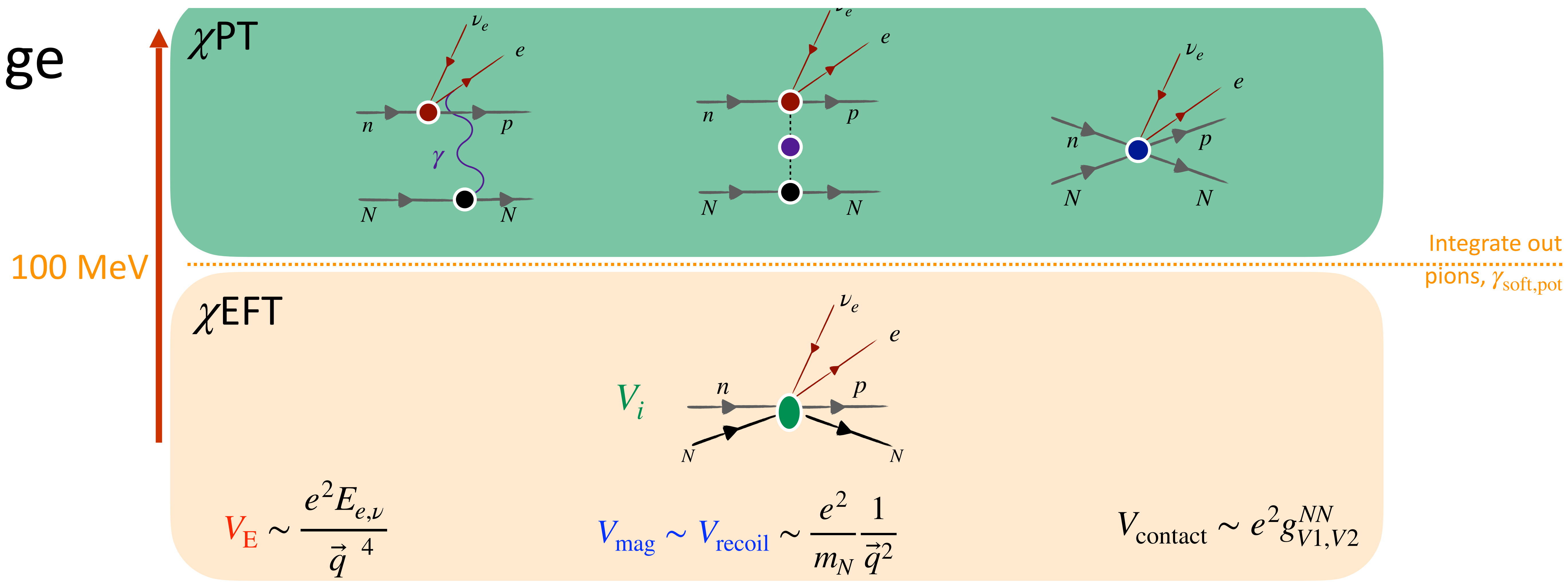
Ab-initio δ_{NS} for ${}^{10}C \to {}^{10}B$ and ${}^{14}O \to {}^{14}N$ transitions in QMC

Recently: NS correction formulated in EFT language

Unknown Low-Energy Constants parametrize integrated-out physics at higher scales

Only natural-size estimate for LEC viable

$$g^{NN}_{V1,V2} = 1/(4 m_N F_\pi^2)$$



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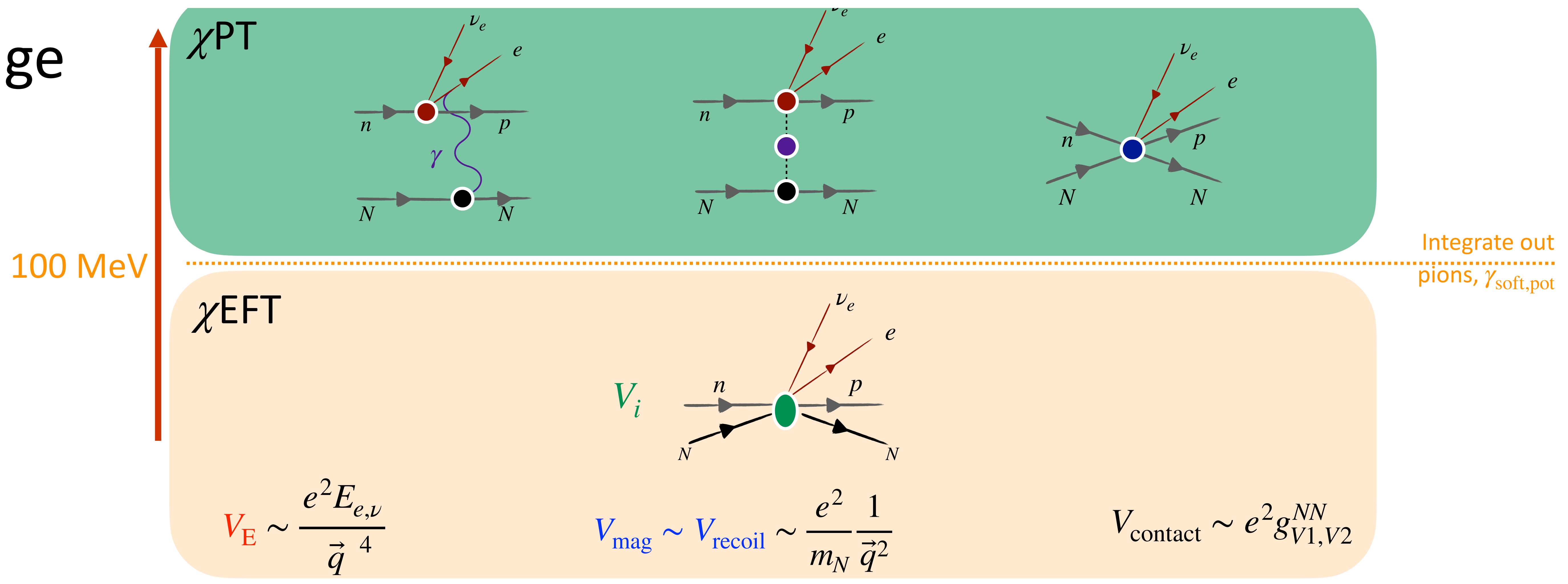

Ab initio theory used to compute m.e. in EFT: Quantum Monte Carlo (QMC) methods (VMC and GFMC)

Independent ab initio calculation for $^{10}C \rightarrow {}^{10}B$ $\quad \delta_{\text{NS}} = -0.429(73)\,\%$ **King et al 2509.07310**

First ab initio calculation for $^{14}O \rightarrow {}^{14}N$ $\quad \delta_{\text{NS}} = -0.187(88)\,\%$ **Cirigliano et al, 2405.18469**

Compare to Hardy-Towner 2020: $\delta_{\text{NS}} = -0.196(50)\,\%$

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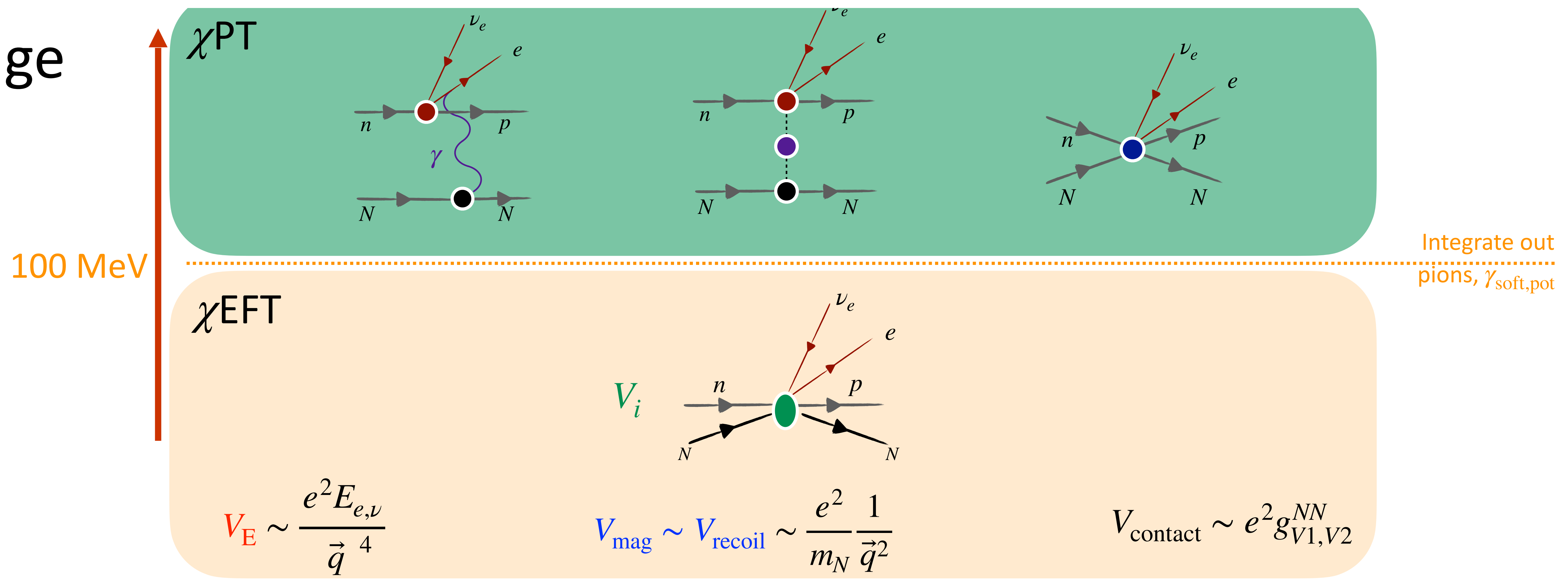
$$g^{NN}_{V1,V2} = 1/(4 m_N F_\pi^2)$$



Ab initio theory used to compute m.e. in EFT: Quantum Monte Carlo (QMC) methods (VMC and GFMC)

Independent ab initio calculation for $^{10}C \to {}^{10}B$ $\qquad \delta_{\text{NS}} = -0.429(73)\,\%$ $\qquad$ **King et al 2509.07310**

First ab initio calculation for $^{14}O \to {}^{14}N$ $\qquad \delta_{\text{NS}} = -0.187(88)\,\%$ $\qquad$ **Cirigliano et al, 2405.18469**

Compare to Hardy-Towner 2020: $\delta_{\text{NS}} = -0.196(50)\,\%$

Recheck NS correction for remaining 13 transitions with **different** methods —> every contribution valuable!

Finite nuclear size effects in δ_C and β spectrum

QED + FNS corrections to β-spectrum

f-value: integrated β spectrum
Q-value small
not measured but computed

$$f = m_e^{-5} \int_{m_e}^{E_0} dE_e \, |\vec{p}_e| E_e (E_0 - E_e)^2 F(E_e) C(E_e) Q(E_e) R(E_e) r(E_e)$$

Unperturbed beta spectrum

Pure QED

Depend on finite nuclear size
Fermi function F: e^+ in Coulomb field
Shape factor C: spatial distribution of decay

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Unperturbed beta spectrum

Pure QED

Depend on finite nuclear size
Fermi function F: e^+ in Coulomb field
Shape factor C: spatial distribution of decay

Traditionally: assumed decay probability equally distributed across the nucleus, $\rho_{\rm cw} \approx \rho_{\rm ch}$

But: Isospin symmetry + known charge distributions of T=1 members implies

$0^+, T=1, T_z=-1$ → $0^+, T=1, T_z=0$ → $0^+, T=1, T_z=1$

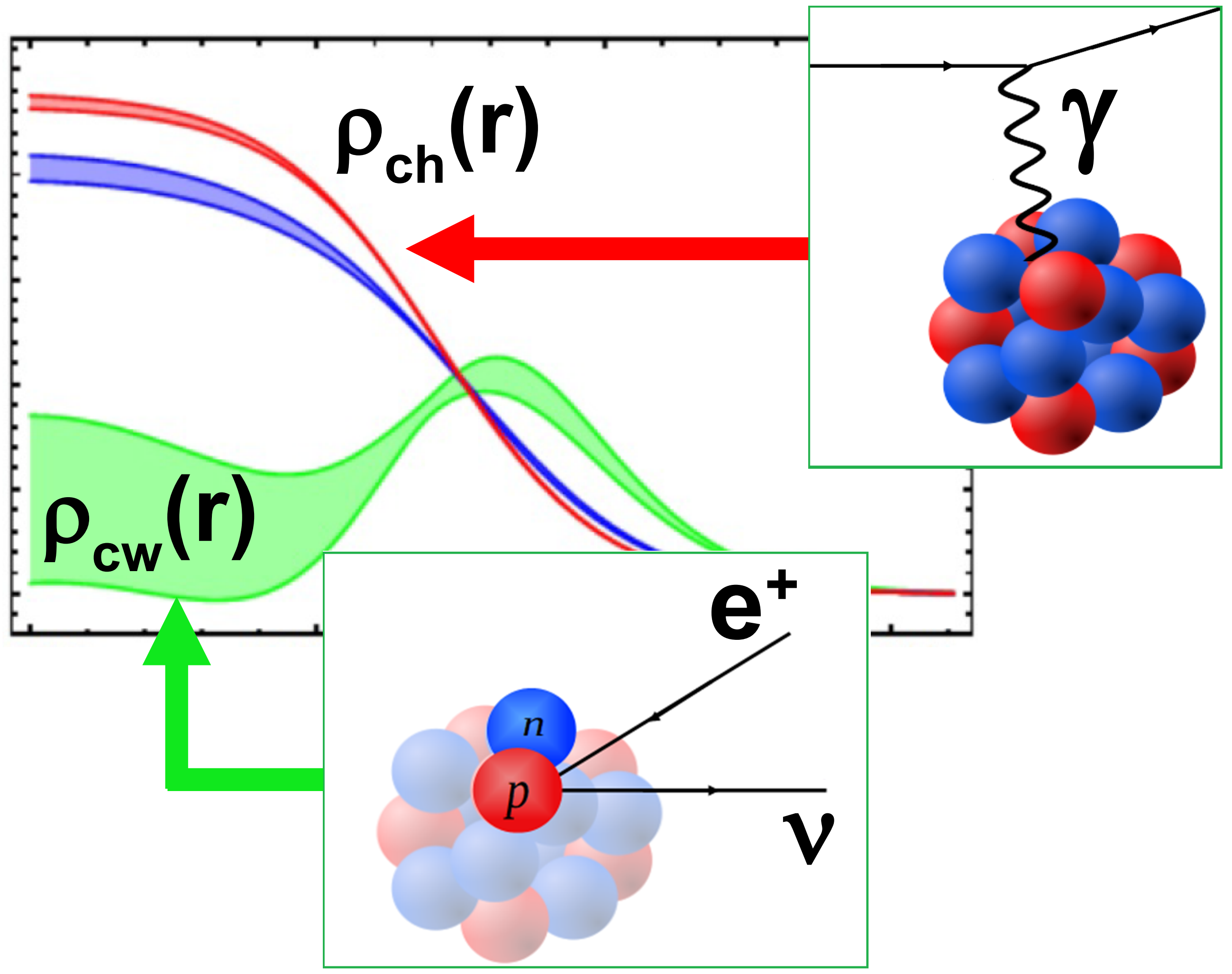
$$\rho_{cw} = Z_0 \rho_{ch}^{T_z=0} - Z_1 \rho_{ch}^{T_z=1} = \frac{1}{2}\left[Z_{-1}\rho_{ch}^{T_z=-1} - Z_1 \rho_{ch}^{T_z=1} \right]$$

Photon probes the entire nuclear charge

Only outer protons can decay: all neutron states in the core occupied

Transition density has much larger radius

Seng, 2212.02681
MG, Seng 2311.16755



One radius makes a difference in BSM search!

Recent measurement at ISOLDE: isotope Shift in Al 27-26m atoms **Plattner et al, 2310.15291**

$$R_c(^{26m}\mathrm{Al}) = 3.130(15)\ \mathrm{fm}$$

Previously guessed (HT) $R_c(^{26m}Al) = 3.040(20)\,\mathrm{fm}$

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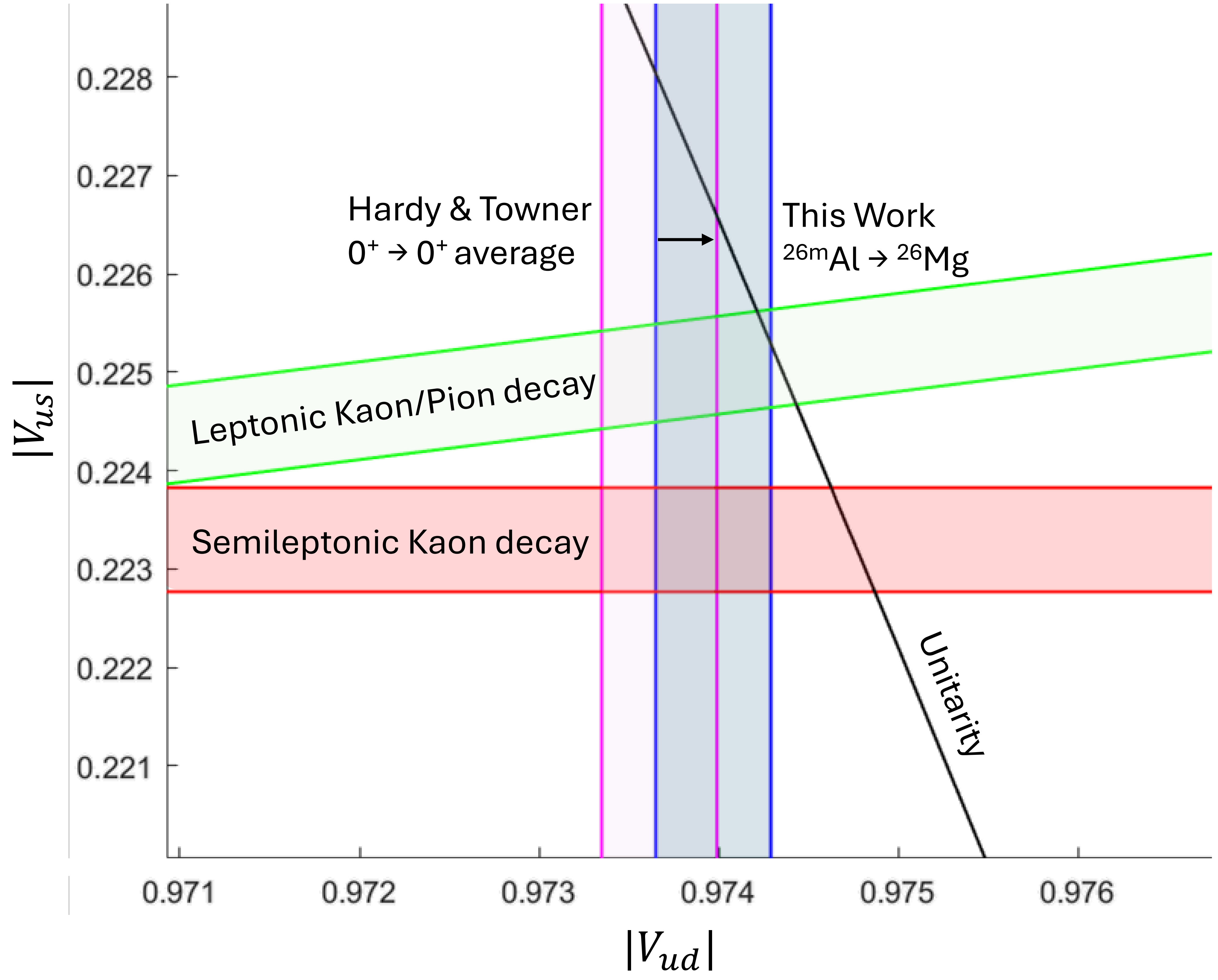
MG et al, 2502.17070

Re-examined ~ALL ingredients (measurement —> radii —> Vud)

$$|V_{ud}|^2 + |V_{us}|^2 = 0.9985(7) \longrightarrow |V_{ud}|^2 + |V_{us}|^2 = 0.9991(7)$$

Impact of precise nuclear radii on V_{ud} demonstrated

But: only f was revisited; need to check δ_{NS} and δ_C

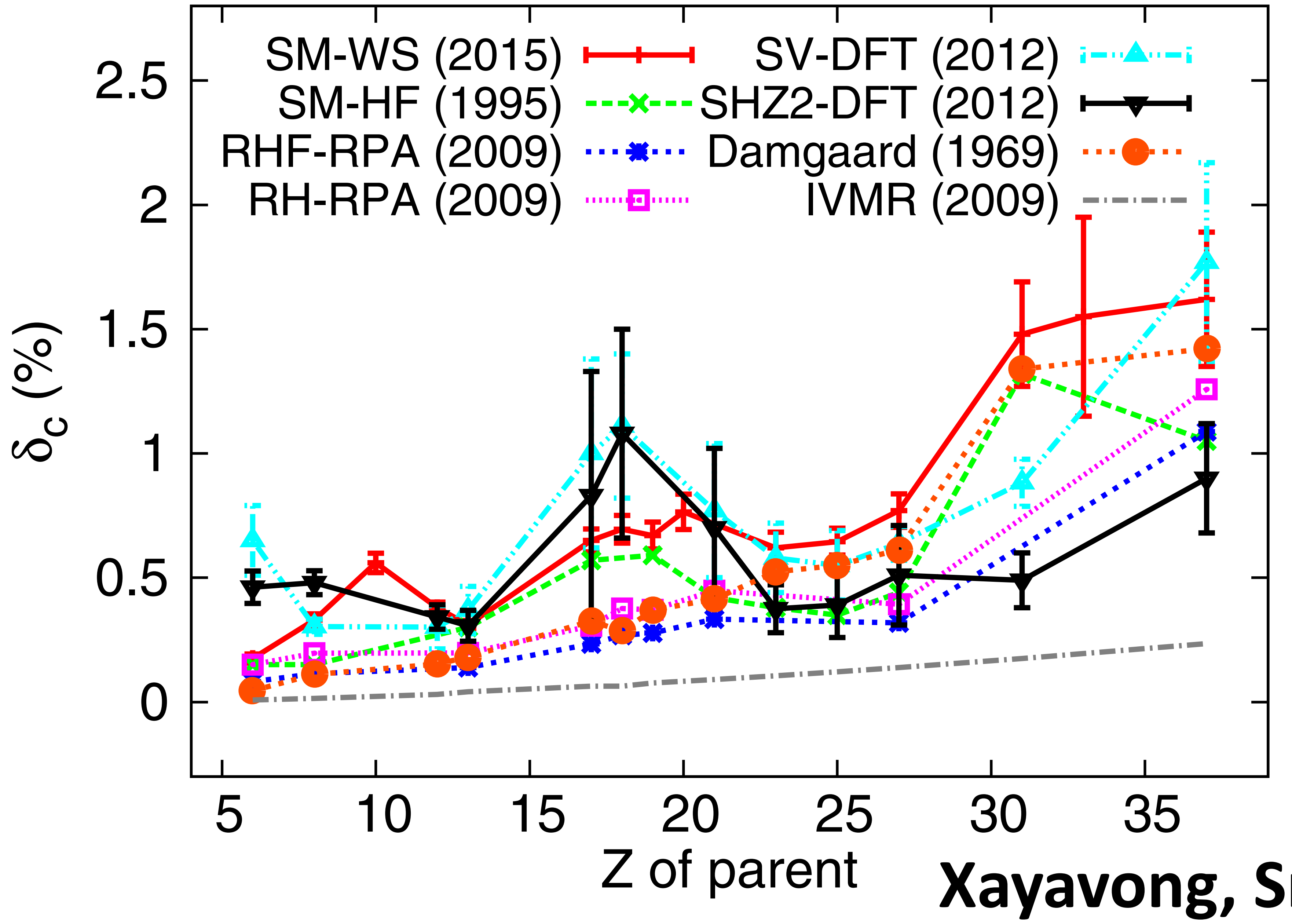


Isospin-breaking correction δ_C in nuclear models

			RPA				
	SM-WS	SM-HF	PKO1	DD-ME2	PC-F1	IVMR[a]	DFT
$T_z = -1$							
^{10}C	0.175	0.225	0.082	0.150	0.109	0.147	0.650
^{14}O	0.330	0.310	0.114	0.197	0.150		0.303
^{22}Mg	0.380	0.260					0.301
^{34}Ar	0.695	0.540	0.268	0.376	0.379		
^{38}Ca	0.765	0.620	0.313	0.441	0.347		
$T_z = 0$							
^{26m}Al	0.310	0.440	0.139	0.198	0.159		0.370
^{34}Cl	0.650	0.695	0.234	0.307	0.316		
^{38m}K	0.670	0.745	0.278	0.371	0.294	0.434	
^{42}Sc	0.665	0.640	0.333	0.448	0.345		0.770
^{46}V	0.620	0.600					0.580
^{50}Mn	0.645	0.610					0.550
^{54}Co	0.770	0.685	0.319	0.393	0.339		0.638
^{62}Ga	1.475	1.205					0.882
^{74}Rb	1.615	1.405	1.088	1.258	0.668		1.770
χ^2/ν	1.4	6.4	4.9	3.7	6.1		4.3[b]

Hardy, Towner, Phys.Rev. C 91 (2014), 025501

δ_C crucial for alignment of Ft values but model dependence



Xayavong, Smirnova, 1708.00616

HT: χ^2 as criterion to prefer SM-WS;

—> V_{ud} and BSM intertwined with nuclear models!

Nuclear community embarked on ab-initio δ_C calculations

Complement with independent test: data-driven approach to benchmark model calculations

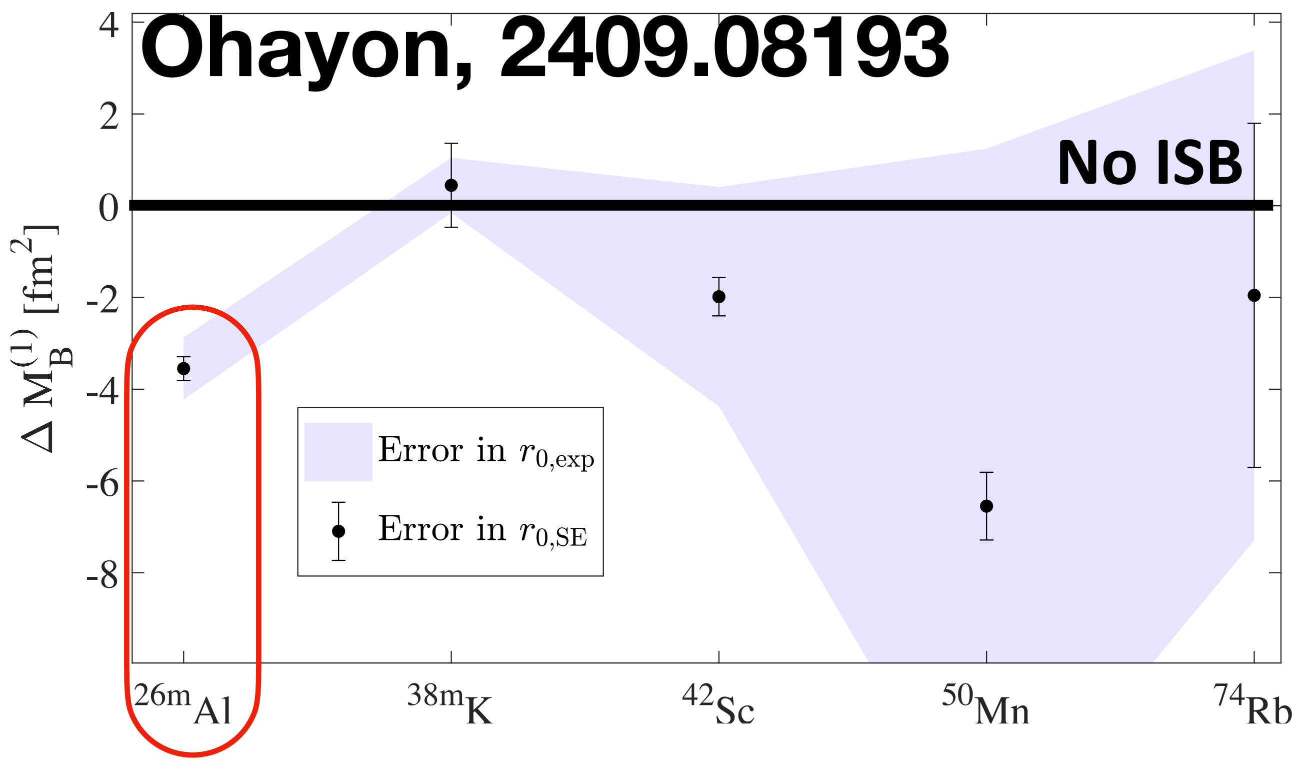
Data-Driven δ_C from nuclear radii

ISB-sensitive combinations of nuclear radii across isotriplet

Seng, MG 2208.03037; 2304.03800; 2212.02681

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2$$

$\Delta M_B^{(1)} = 0$ used for ft-value in isospin limit



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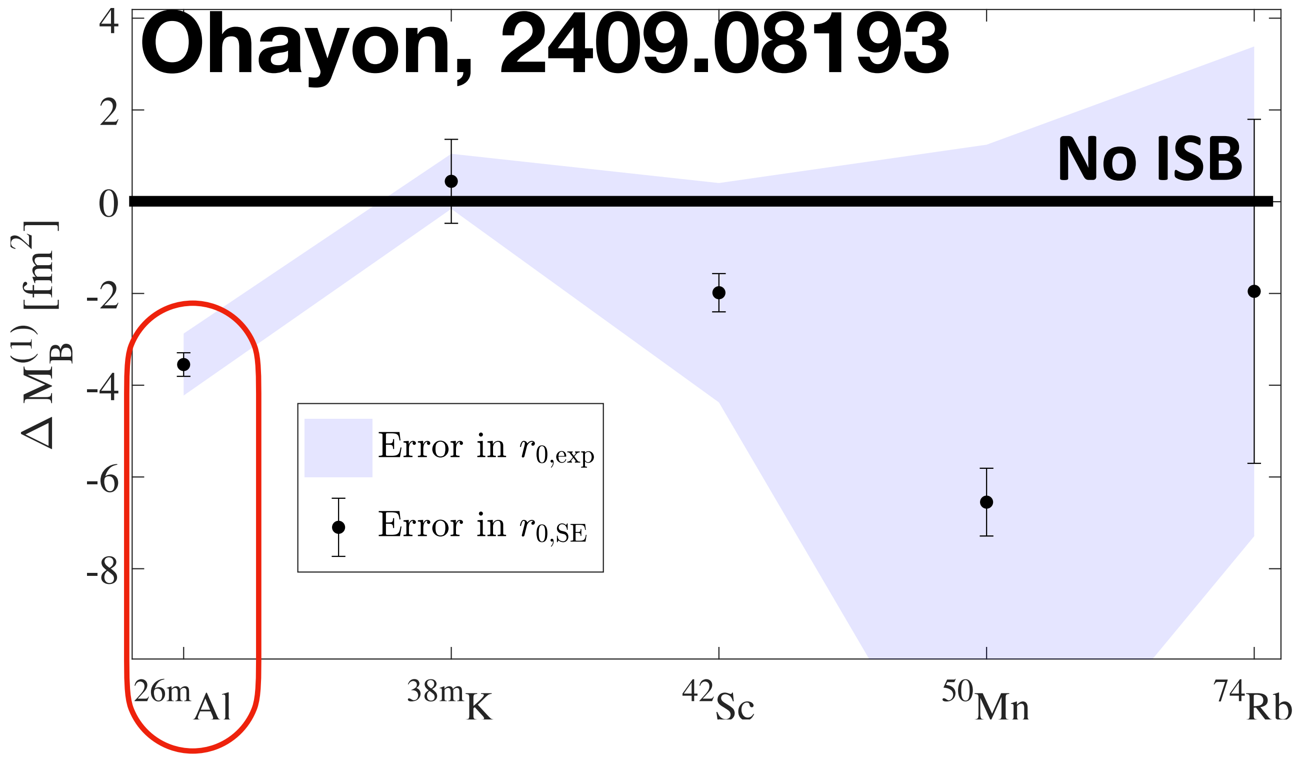


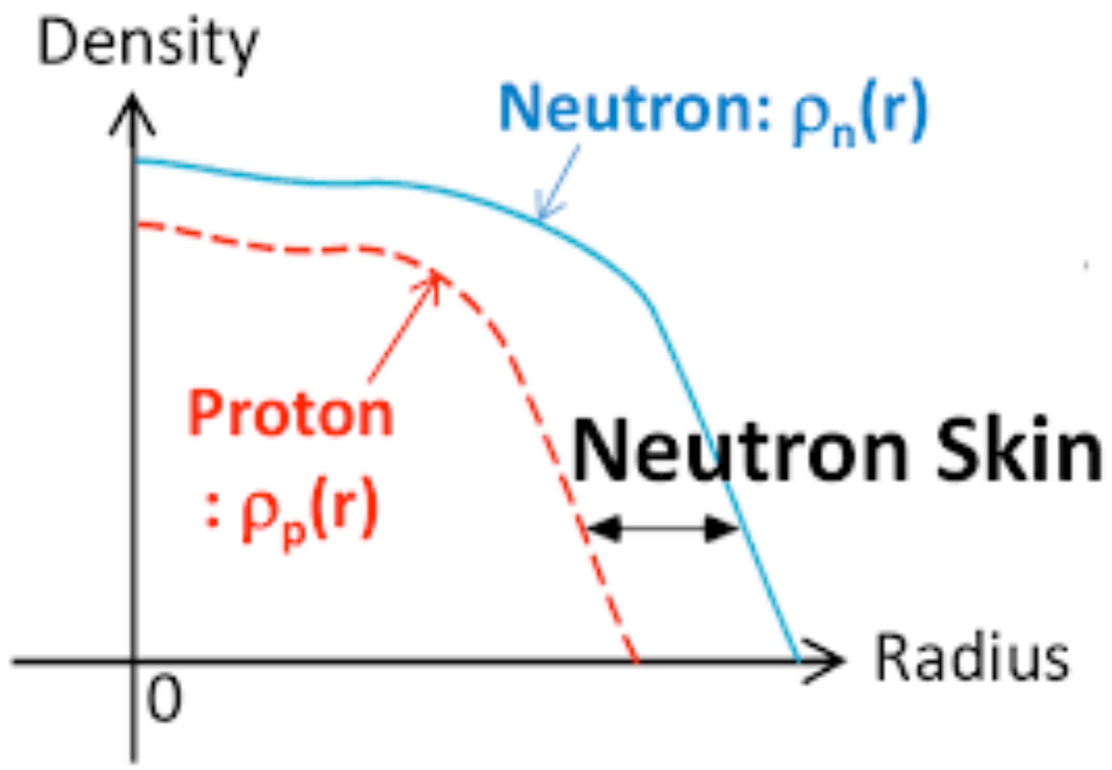
Another combination uses neutron radius

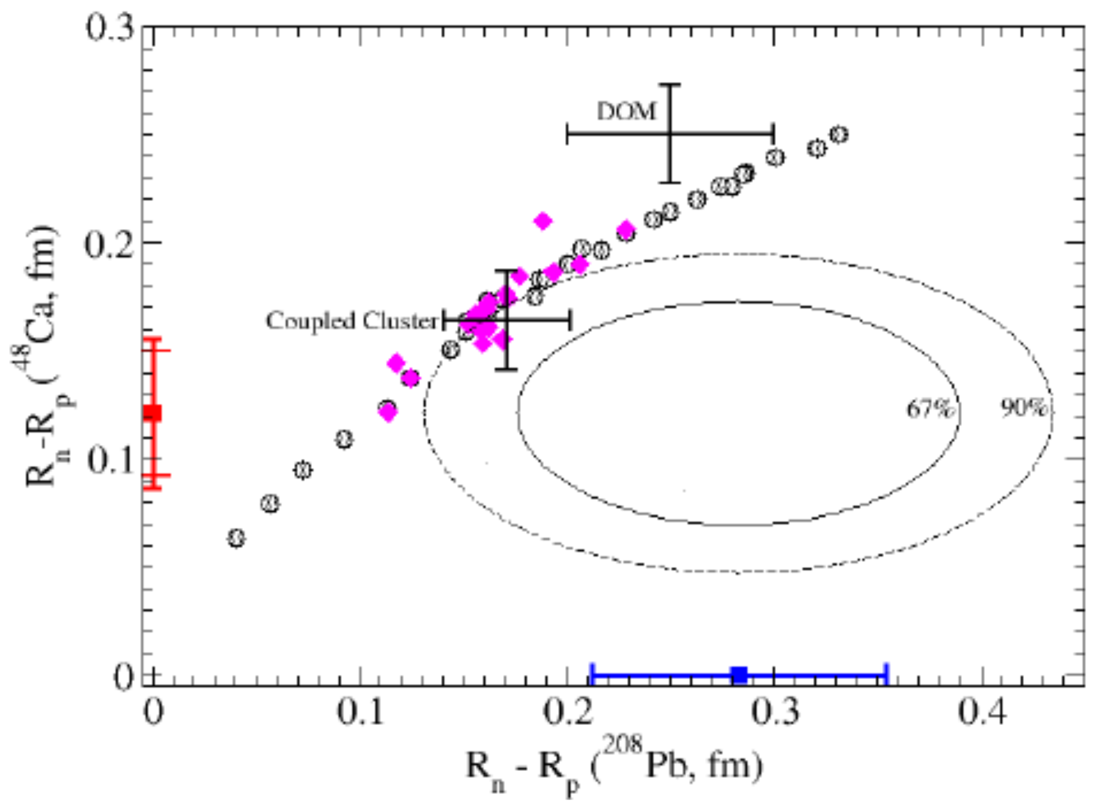
$$\Delta M_A^{(1)} \equiv -\langle r_{\mathrm{CW}}^2\rangle + \left(\frac{N_1}{2}\langle r_{n,1}^2\rangle - \frac{Z_1}{2}\langle r_{p,1}^2\rangle\right)$$

Neutron radius accessible with PV e-scattering

PV asymmetry ~ $\langle r_{n,1}^2\rangle - \langle r_{p,1}^2\rangle$ - neutron skin

Studies in neutron rich nuclei <—> neutron stars





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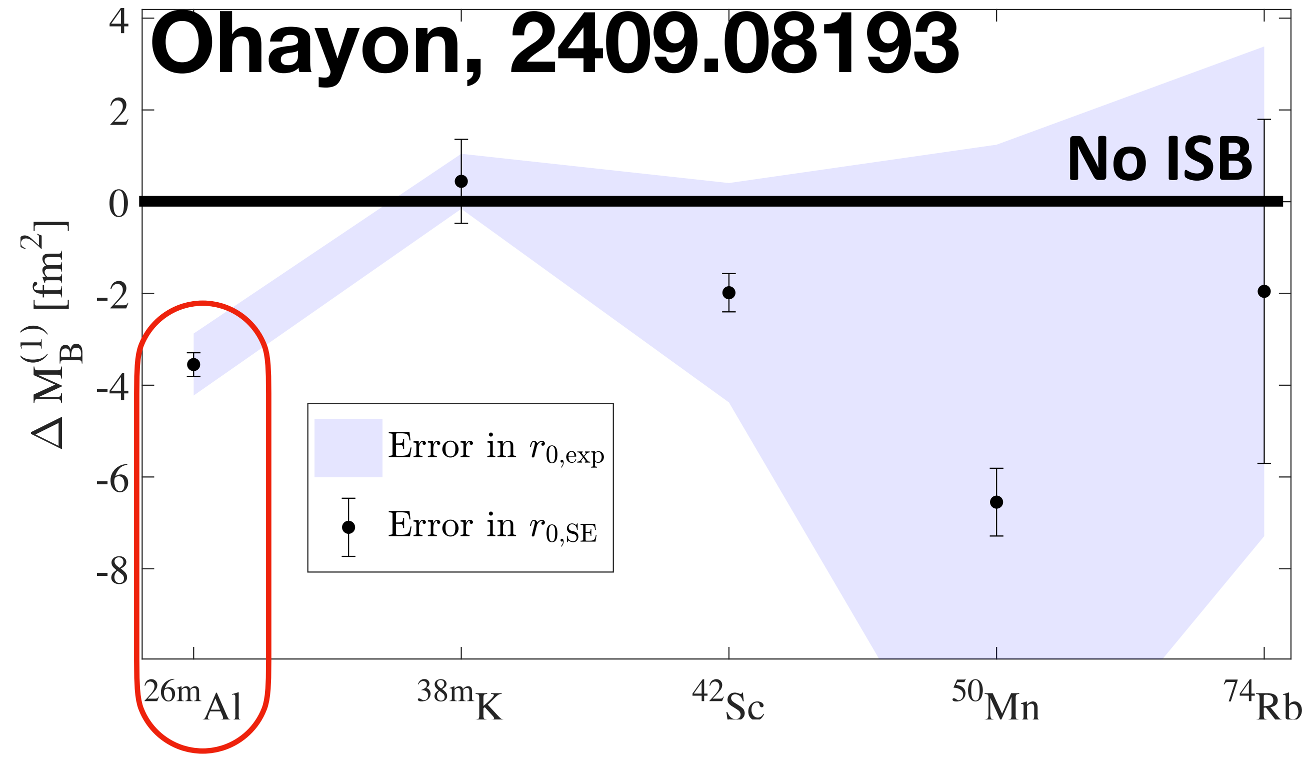

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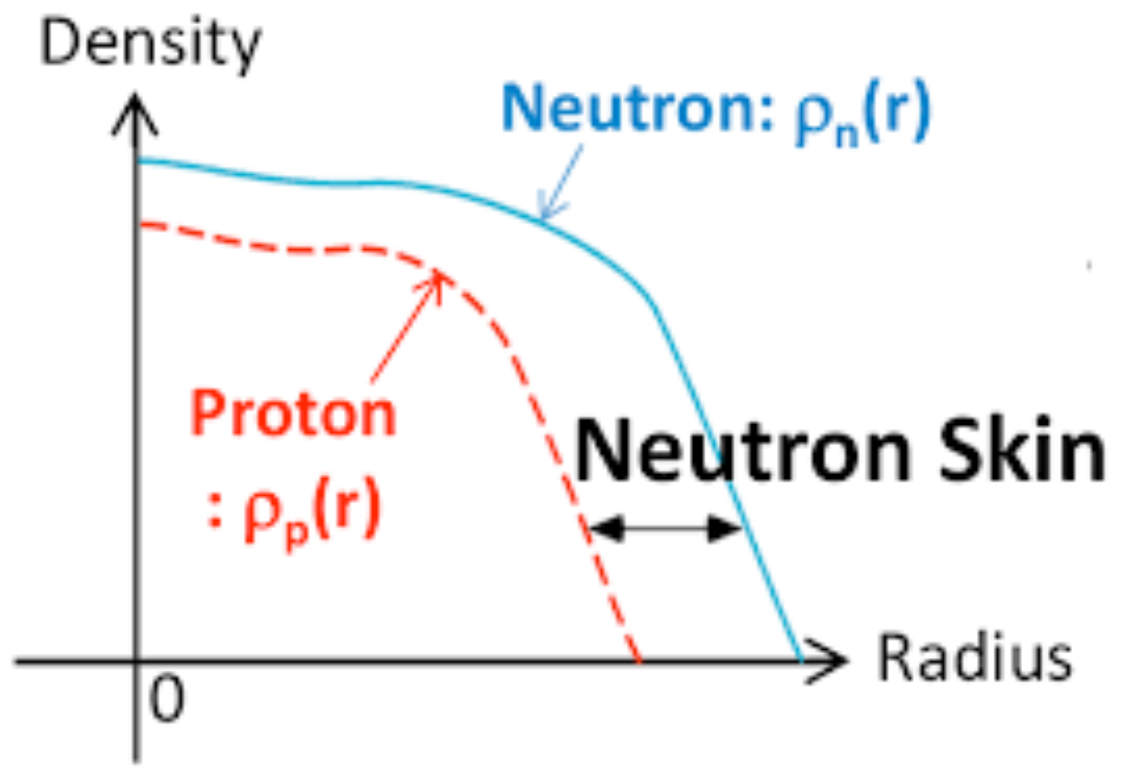
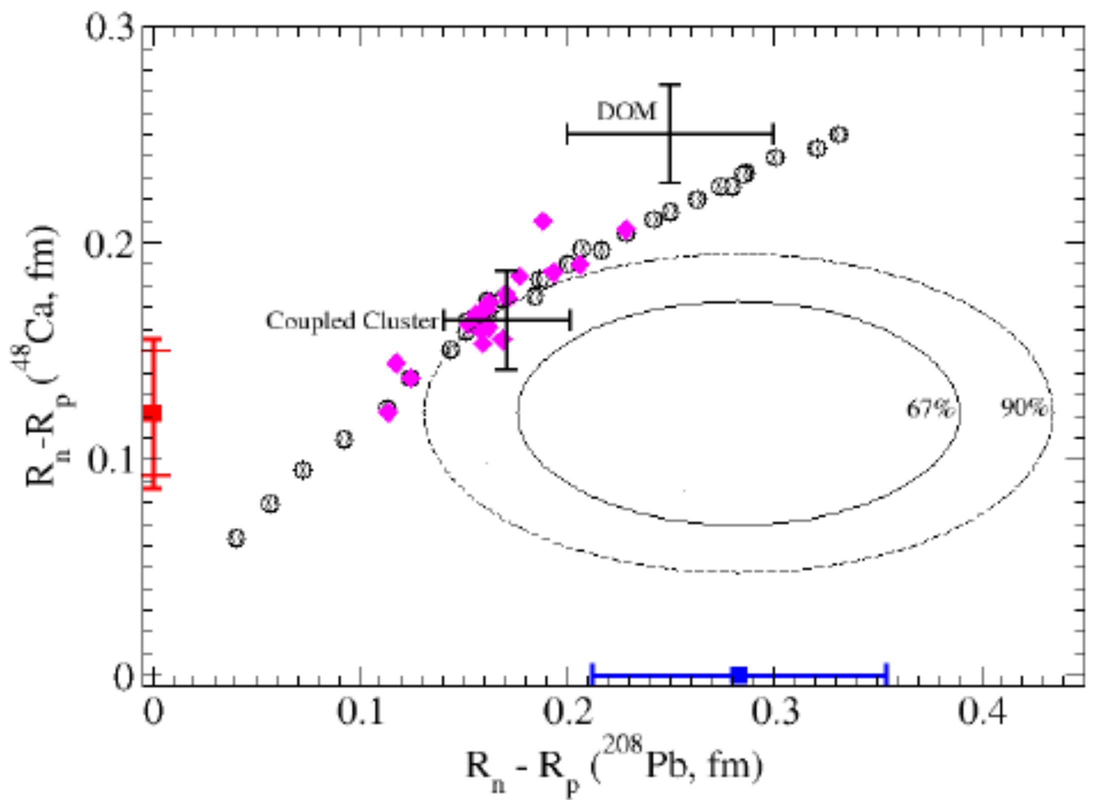




Upcoming exp. program at Mainz (MREX):
neutron skins of stable daughters (e.g. Mg-26, Ca-42, Fe-54)
Sub-% measurement of R_n feasible (case study C-12)

N. Cargioli, MG et al, 2407.09743

Summary

- In Standard Model measurements are not independent —> overconstrained
- This being overconstrained is the basis for precision tests, BSM removes degeneracy!
- Tests of Cabibbo unitarity at 0.01% require hadronic corrections to 10%
- BSM interpretations:
  RH currents with non-trivial light flavor structure
  Superallowed decays alone: sensitivity to scalar BSM complementary to colliders
- Interplay of experiment, LQCD and EFT theory and data-driven methods
- Nuclear theory community embarked on re-evaluation of nuclear corrections
  with modern ab-initio methods
- New synergies with atomic physics (charge radii) and PV e-scattering (neutron skins) identified

Outlook

Exciting times: improved measurements of neutron decay imminent (but: discrepancies!), pion in ~10 years

Effort of nuclear theory community to keep superallowed decays leadership

Cooperation across nuclear, particle, atomic physics with new initiatives in **HADRON 2030 (Horizon Europe)**

FITTED: global electroweak fit in SM and beyond (collider and low-energy observables)

RADIANT: new interactive table of nuclear charge radii as a community effort with support by IAEA

https://doi.org/10.61092/iaea.vm5h-hmep

IAEA International Atomic Energy Agency

INDC(NDS)-0918
Distr. G,MP

INDC International Nuclear Data Committee

Compilation and Evaluation of Nuclear Charge Radii

Summary Report of the Technical Meeting

IAEA Headquarters, Vienna, Austria
27–30 January 2025

Prepared by

K. Flanagan
University of Manchester
Manchester, UK

H. Staiger
Clemson University
Clemson, SC, USA

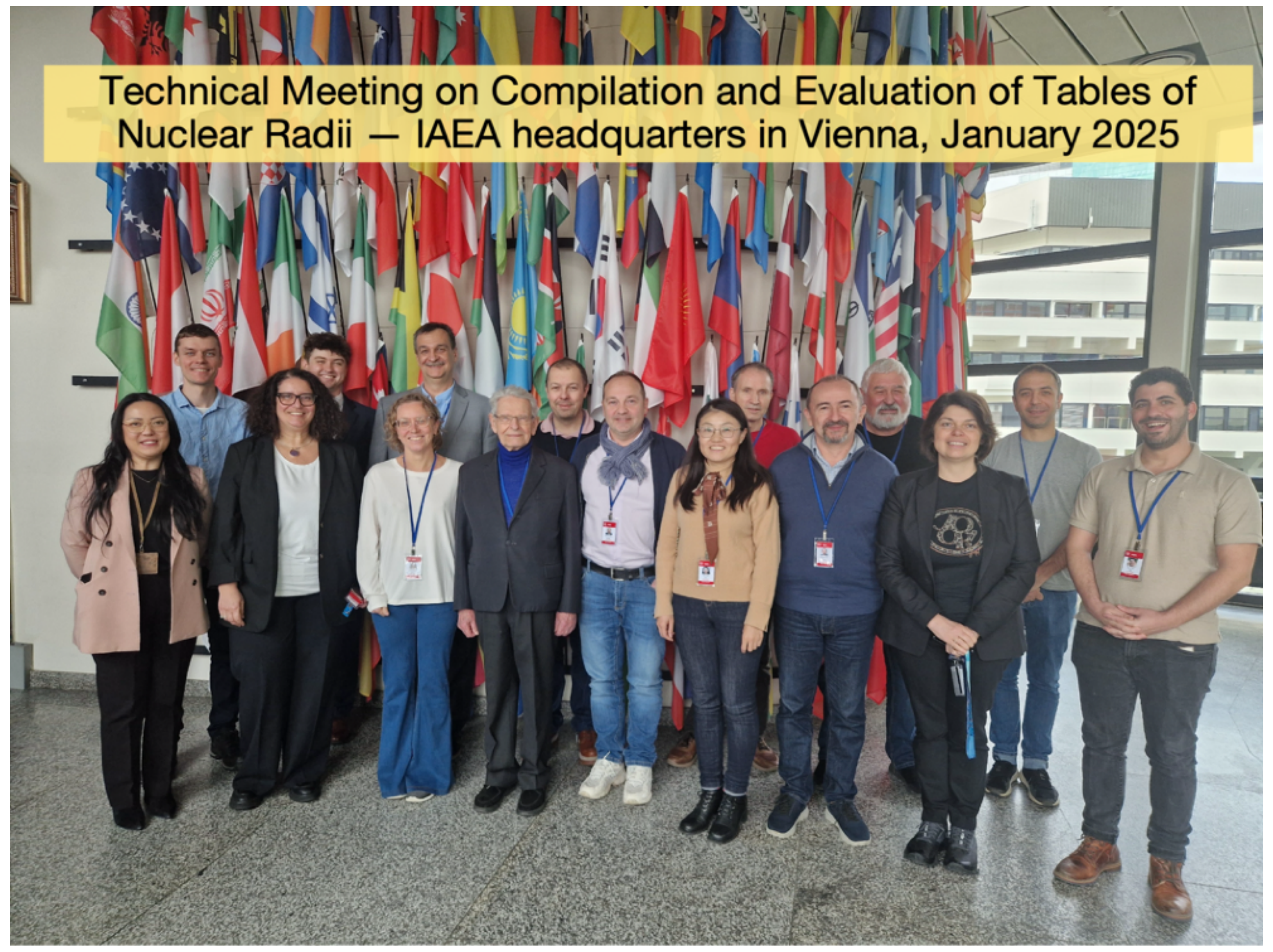
E. Takacs
Clemson University
Clemson, SC, USA

P. Dimitriou
International Atomic Energy Agency
Vienna, Austria

June 2025

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

https://nds.iaea.org/publications/indc/indc-nds-0918/



4. RECOMMENDATIONS

Based on the presentations and subsequent discussions, participants formulated the following list of recommendations, which they considered crucial for creating a new table of recommended nuclear charge radii that is both functional and easy to maintain:

- We recommend regular updates and maintenance of the database with all data and enhancing dissemination using modern web interfaces and database technologies.
- We recommend creating a working group that will regularly meet to advise on developments, updates, and dissemination of the database. It should contain data producers, evaluators, and user representatives.
- There is a need for a white paper with detailed recommendations describing the visions and future directions of the field and the future evaluation.
- We encourage the reanalysis of existing data using modern theoretical and statistical techniques, *(for example dispersion correction in electron scattering, nuclear polarization in muonic atoms, and others)*.
- There is a need for additional support from stakeholders for experimental and theoretical groups in acquiring new data as well as developing new and improving existing theoretical frameworks.
- We recommend training the next generation of experts in nuclear charge radii and evaluation.
- Since this database is complementary to the nuclear moments and transition's probability databases, we recommend the results of this effort are communicated to the nuclear structure and decay data network.