Dispersion Theory of the γW-Box Correction to Nuclear β-Decays

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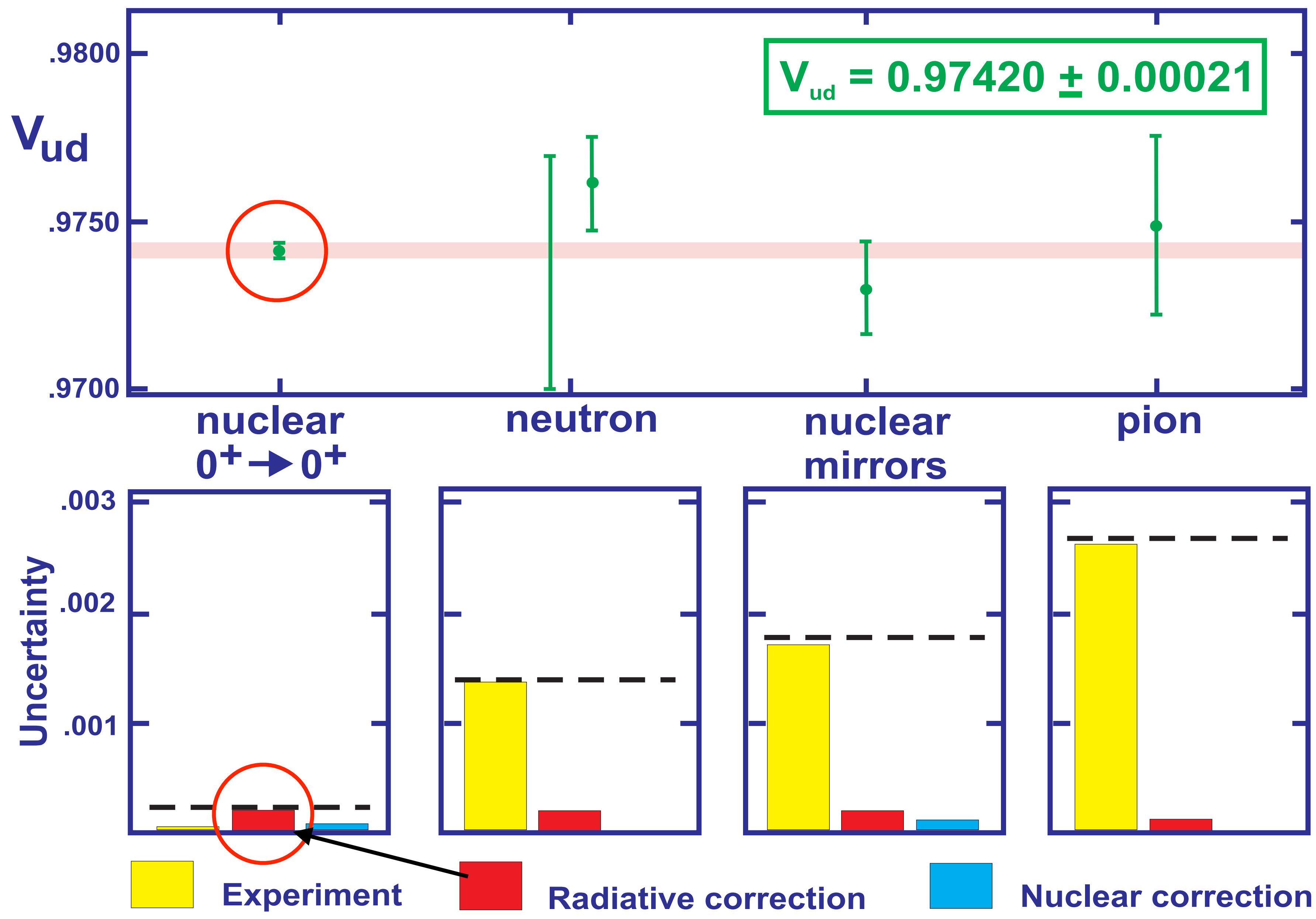
Based on 3 papers:

arXiv: 1807.10197
arXiv: 1812.03352
arXiv: 1812.04229

Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

Precise beta decay calculations for searches for new physics
Trento, April 8-12, 2019

Current status of V_{ud} and CKM unitarity



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005$$

0^+-0^+ nuclear decays $|V_{ud}|^2 = 0.94906 \pm 0.00041$

K decays $|V_{us}|^2 = 0.05031 \pm 0.00022$

B decays $|V_{ub}|^2 = 0.00002$

CKM unitarity: V_{ud} the main contributor to the sum and to the uncertainty

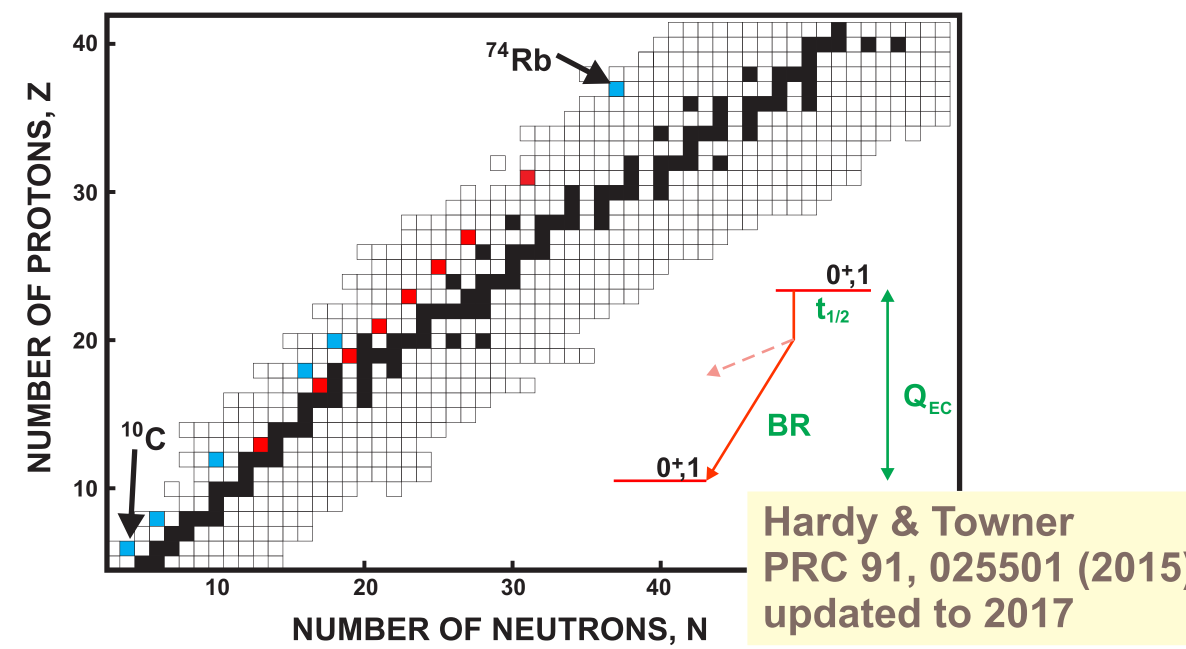
Why are superallowed decays special?

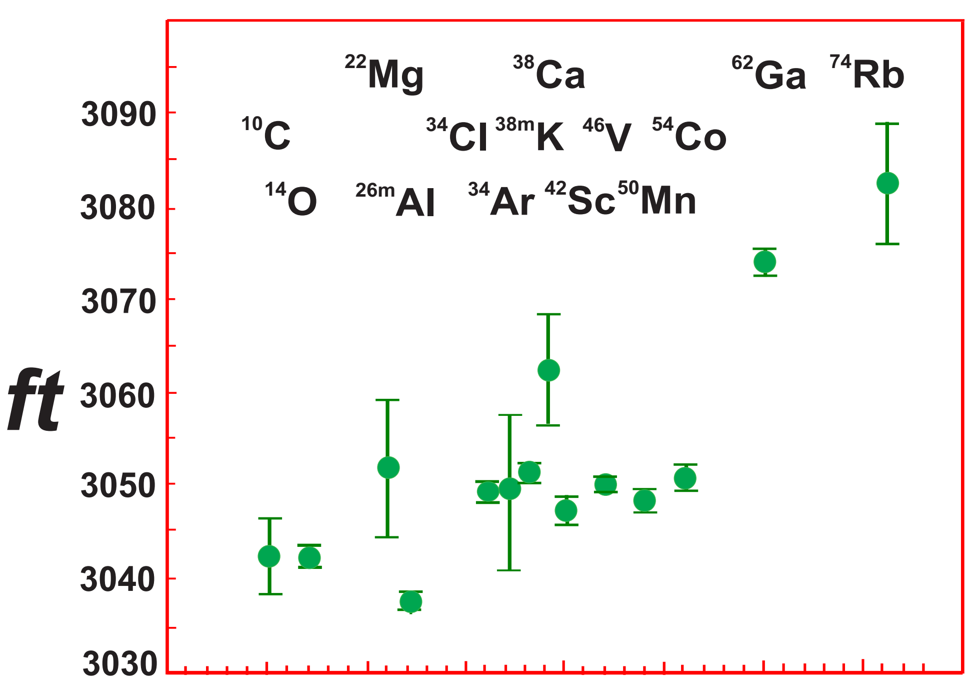
Superallowed 0^+-0^+ nuclear decays:

- only conserved vector current (unlike the neutron decay and other mirror decays)
- many decays (unlike pion decay)
- all decay rates should be the same modulo phase space

Experiment: **f** - phase space (Q value) and **t** - partial half-life ($t_{1/2}$, branching ratio)

- **8 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.**
- **~220 individual measurements with compatible precision**





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

Reason: SU(2) slightly broken

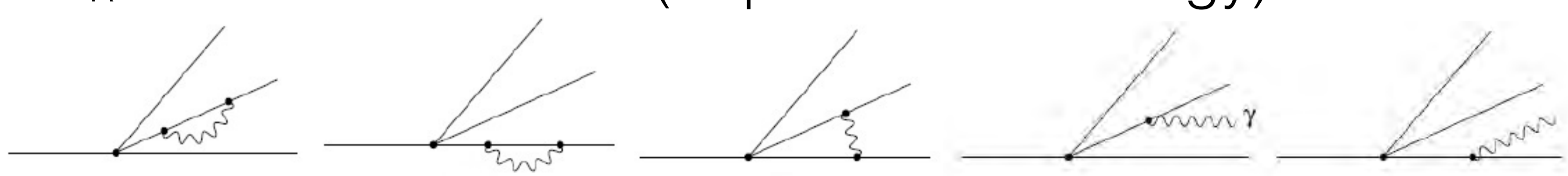
a. RC (e.m. interaction does not conserve isospin)
b. Nuclear WF are not SU(2) symmetric (proton and neutron distribution not the same)

Why are superallowed decays special?

Modified ft-values to include these effects

$$\mathcal{F}t = ft(1+\delta'_R)[1-(\delta_C-\delta_{NS})]$$

δ'_R - "outer" correction (depends on e-energy) - QED



δ_C - SU(2) breaking in the nuclear matrix elements

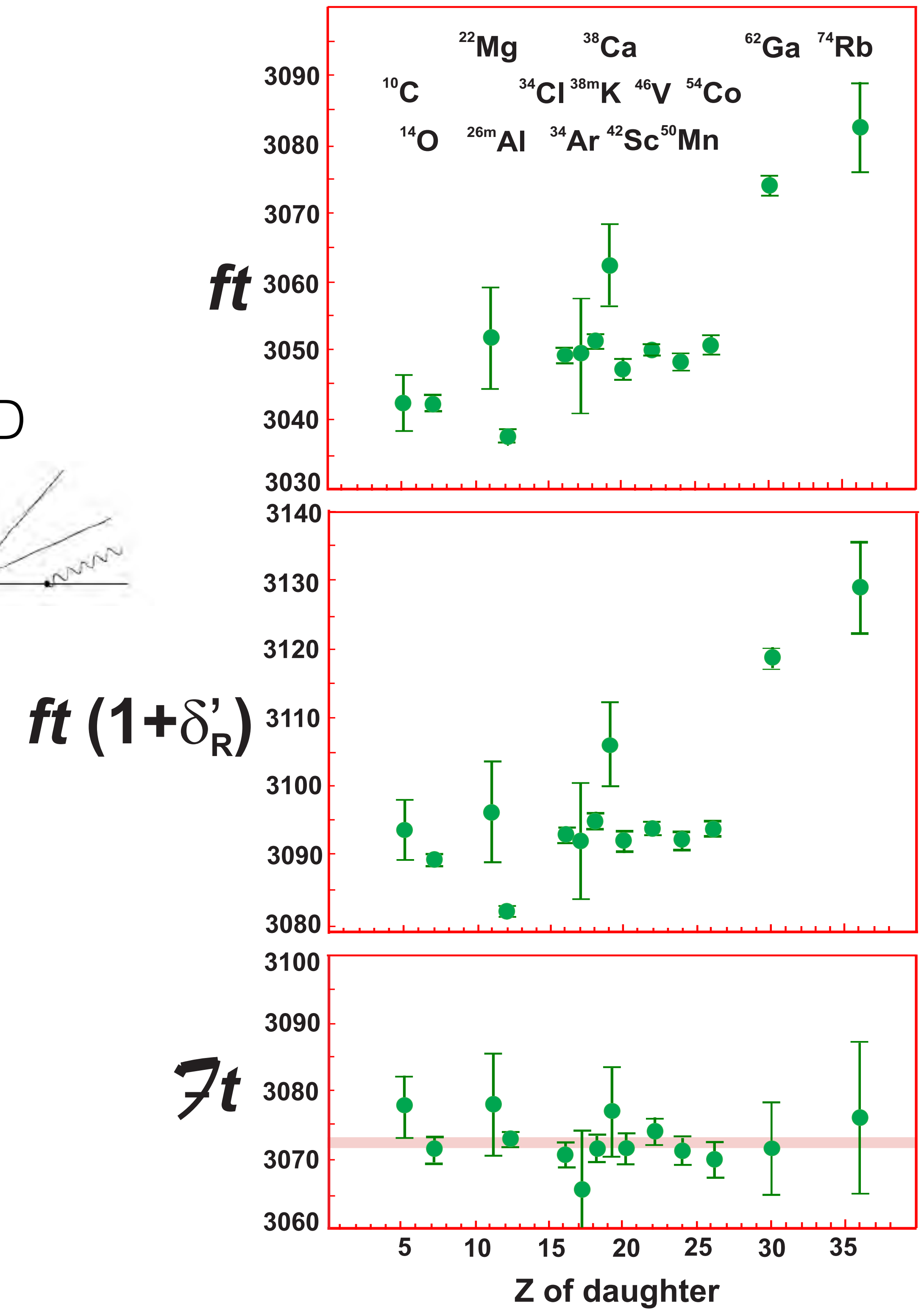
- mismatch of radial WF in parent-daughter
- mixing of different isospin states

δ_{NS} - RC depending on the nuclear structure

δ_C, δ_{NS} - energy independent

Average

$$\overline{\mathcal{F}t} = 3072.1 \pm 0.7$$



Hardy, Towner 1973 - 2018

Corrections to superallowed decays

TABLE X: Corrections δ'_R, δ_{NS} and δ_C that are applied to experimental ft values to obtain $\mathcal{F}t$ values.

Parent nucleus	δ'_R (%)	δ_{NS} (%)	δ_{C1} (%)	δ_{C2} (%)	δ_C (%)
$T_z = -1$:					
^{10}C	1.679	−0.345(35)	0.010(10)	0.165(15)	0.175(18)
^{14}O	1.543	−0.245(50)	0.055(20)	0.275(15)	0.330(25)
^{18}Ne	1.506	−0.290(35)	0.155(30)	0.405(25)	0.560(39)
^{22}Mg	1.466	−0.225(20)	0.010(10)	0.370(20)	0.380(22)
^{26}Si	1.439	−0.215(20)	0.030(10)	0.405(25)	0.435(27)
^{30}S	1.423	−0.185(15)	0.155(20)	0.700(20)	0.855(28)
^{34}Ar	1.412	−0.180(15)	0.030(10)	0.665(55)	0.695(56)
^{38}Ca	1.414	−0.175(15)	0.020(10)	0.745(70)	0.765(71)
^{42}Ti	1.427	−0.235(20)	0.105(20)	0.835(75)	0.940(78)
$T_z = 0$:					
^{26m}Al	1.478	0.005(20)	0.030(10)	0.280(15)	0.310(18)
^{34}Cl	1.443	−0.085(15)	0.100(10)	0.550(45)	0.650(46)
^{38m}K	1.440	−0.100(15)	0.105(20)	0.565(50)	0.670(54)
^{42}Sc	1.453	0.035(20)	0.020(10)	0.645(55)	0.665(56)
^{46}V	1.445	−0.035(10)	0.075(30)	0.545(55)	0.620(63)
^{50}Mn	1.444	−0.040(10)	0.035(20)	0.610(50)	0.645(54)
^{54}Co	1.443	−0.035(10)	0.050(30)	0.720(60)	0.770(67)
^{62}Ga	1.459	−0.045(20)	0.275(55)	1.20(20)	1.48(21)
^{66}As	1.468	−0.060(20)	0.195(45)	1.35(40)	1.55(40)
^{70}Br	1.486	−0.085(25)	0.445(40)	1.25(25)	1.70(25)
^{74}Rb	1.499	−0.075(30)	0.115(60)	1.50(26)	1.62(27)

Hardy, Towner 2015

Outline: RC to Beta Decay

$$|V_{ud}|^2 = \frac{2984.432(3)}{\mathcal{F}t(1+\Delta_R^V)}$$

$$\mathcal{F}t = ft(1+\delta'_R)[1-(\delta_C-\delta_{NS})]$$

Three caveats:

1. Calculation of the universal free-neutron RC Δ_R^V **See talk by Chien Yeah**

2. Splitting the full nuclear RC into free-neutron Δ_R^V and nuclear modification δ_{NS}

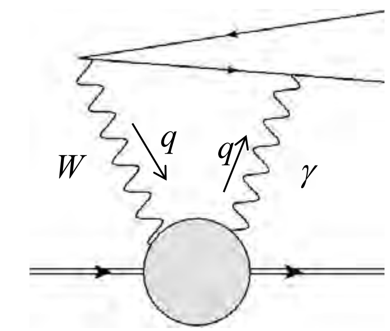
3. Splitting the full RC into "outer" (energy-dependent but pure QED: no hadron structure) and "inner" (hadron&nuclear structure-dependent but energy-independent)
   - nucleon and nuclear case

Will address points 2. and 3.

Will introduce the dispersion formalism first

1. γW-box from dispersion relations

γW-box



Box at zero momentum transfer* (but with energy dependence)

$$T_{\gamma W} = \sqrt{2}e^2 G_F V_{ud} \int \frac{d^4q}{(2\pi)^4} \frac{\bar{u}_e \gamma^\mu (\not{k} - \not{q} + m_e)\gamma^\nu (1-\gamma_5) v_\nu}{q^2[(k-q)^2 - m_e^2]} \frac{M_W^2}{q^2 - M_W^2} T^{\gamma W}_{\mu\nu}$$

***Precision goal: 10^{-4}; RC ~ $\alpha/2\pi$ ~ 10^{-3}; recoil on top - negligible**

Hadronic tensor: two-current correlator

$$T^{\mu\nu}_{\gamma W} = \int dx e^{iqx} \langle f | T[J^\mu_{em}(x) J^{\nu,\pm}_W(0)] | i \rangle$$

General gauge-invariant decomposition of a spin-independent tensor

$$T^{\mu\nu}_{\gamma W} = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) T_1 + \frac{1}{(p\cdot q)}\left(p - \frac{(p\cdot q)}{q^2} q\right)^\mu \left(p - \frac{(p\cdot q)}{q^2} q\right)^\nu T_2 + \frac{i\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta}{2(p\cdot q)} T_3$$

Loop integral with generally unknown forward amplitudes

$$T_{\gamma W} = -\frac{\alpha}{2\pi} G_F V_{ud} \int \frac{d^4 q M_W^2}{q^2(M_W^2 - q^2)} \bar{u}_e \gamma_\beta (1-\gamma_5) u_\nu \sum_i C_i^\beta(E, \nu, q^2) T_i^{\gamma W}(\nu, q^2)$$

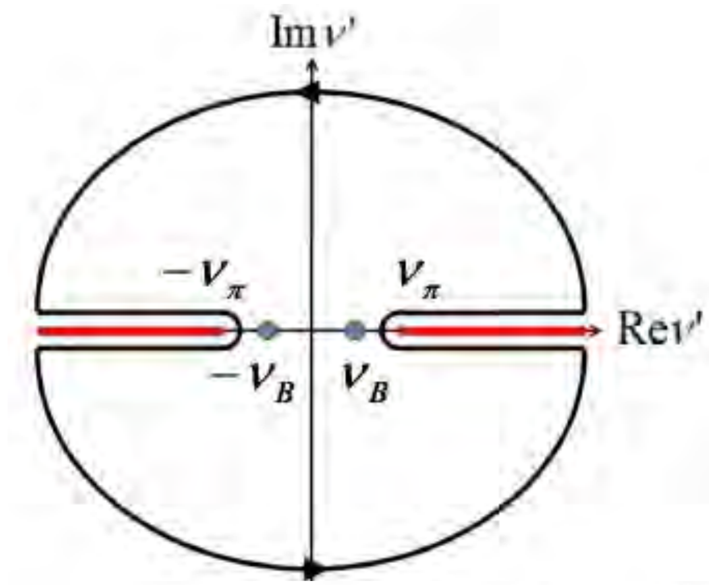
$$p^\mu = (M, \vec{0})$$

$$E = (pk)/M$$

$$\nu = (pq)/M$$

Known algebraic functions of external energy E and loop variables ν, q^2

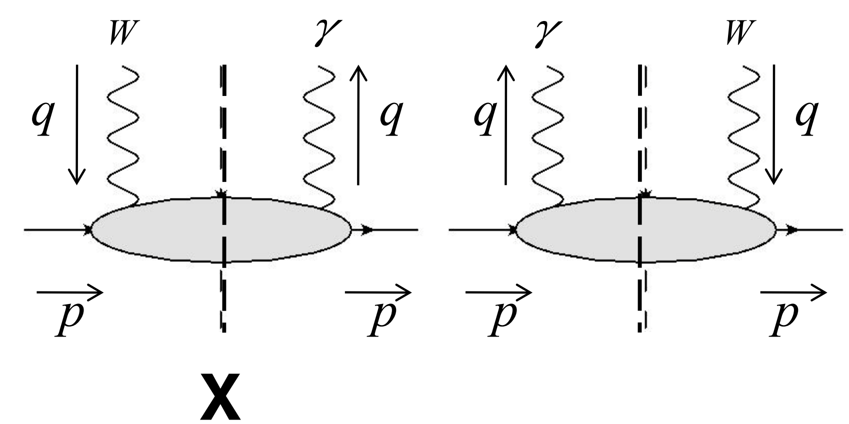
γW-box from Dispersion Relations



$T_{1,2,3}$ - analytic functions inside the contour C in the complex ν-plane determined by their singularities on the real axis - poles + cuts

$$T_i^{\gamma W}(\nu, Q^2) = \frac{1}{2\pi i}\oint dz \frac{T_i^{\gamma W}(z, Q^2)}{z-\nu}, \;\; \nu \in C$$

Forward amplitudes T_i - unknown;
Their absorptive parts can be related to production of on-shell intermediate states
—> a γW-analog of structure functions $F_{1,2,3}$

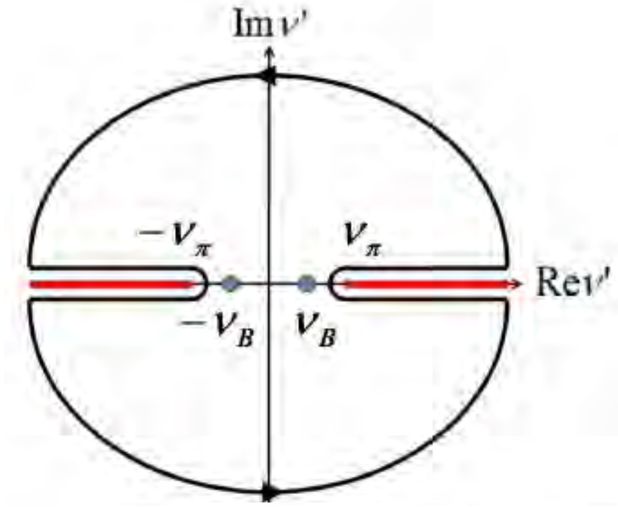


X = inclusive strongly-interacting on-shell physical states

Structure functions $F_i^{\gamma W}$ are NOT data
But they can be related to data

$$\text{Im}\, T_i^{\gamma W}(\nu, Q^2) = 2\pi F_i^{\gamma W}(\nu, Q^2)$$

γW-box from Dispersion Relations



Crossing behavior: relate the left and right hand cut
Mismatch between the initial and final states - asymmetric;
Symmetrize - γ is a mix of I=0 and I=1

$$T_i^{\gamma W,a} = T_i^{(0)}\tau^a + T_i^{(-)}\frac{1}{2}[\tau^3, \tau^a]$$

$$T_i^{(I)}(-\nu, Q^2) = \xi_i^{(I)} T_i^{(I)}(\nu, Q^2)$$

$$\xi_1^{(0)} = +1, \quad \xi_{2,3}^{(0)} = -1; \quad \xi_i^{(-)} = -\xi_i^{(0)}$$

Two types of dispersion relations for scalar amplitudes

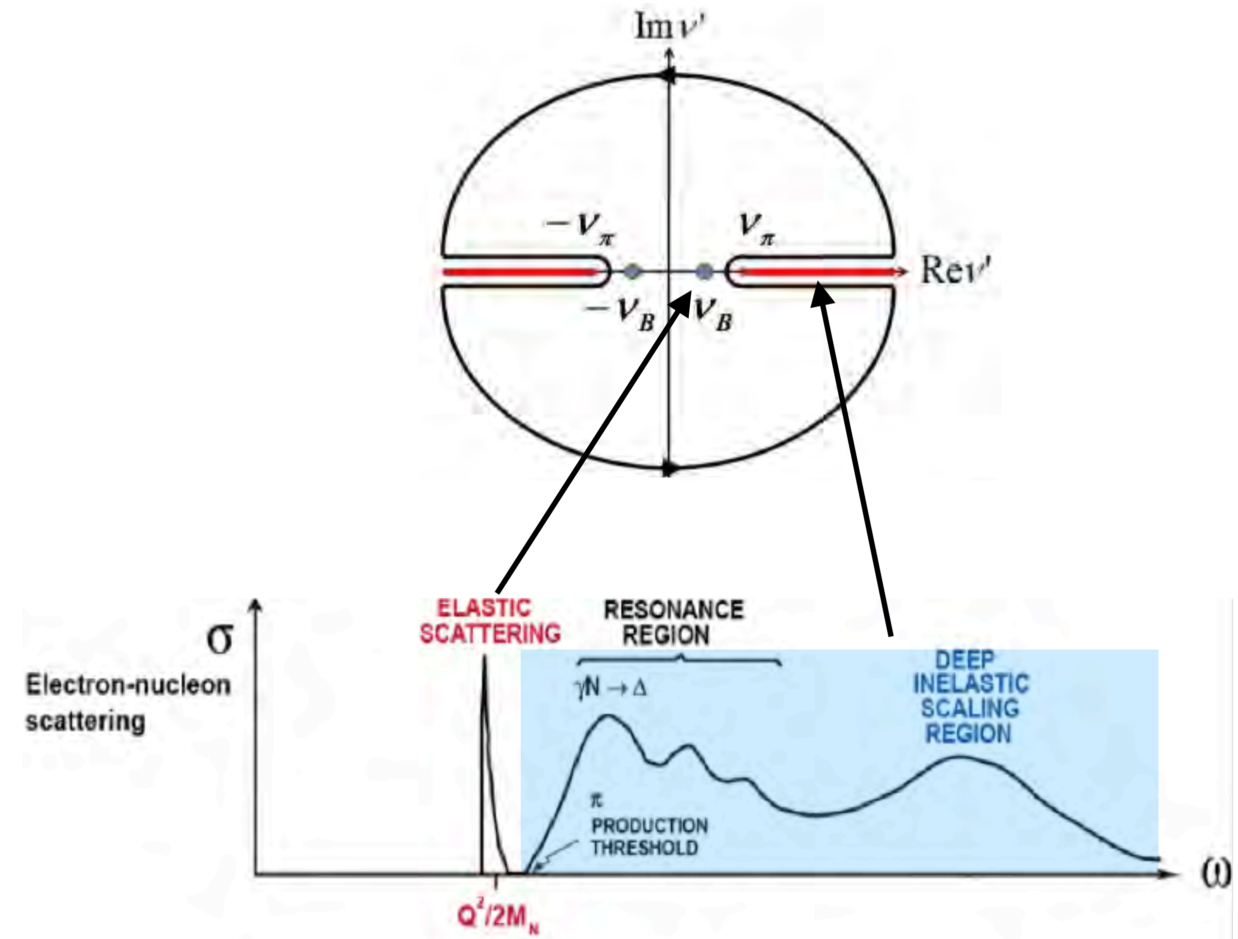
$$T_i^{(I)}(\nu, Q^2) = 2\int_0^\infty d\nu' \left[\frac{1}{\nu' - \nu - i\epsilon} + \frac{\xi_i^{(I)}}{\nu' - \nu - i\epsilon}\right] F_i^{(I)}(\nu', Q^2)$$

Substitute into the loop and calculate leading energy dependence

$$\mathrm{Re}\,\Box_{\gamma W}^{even} = \frac{\alpha}{\pi N}\int_0^\infty dQ^2 \int_{\nu_{thr}}^\infty d\nu \frac{F_3^{(0)}}{M\nu}\frac{\nu + 2q}{(\nu+q)^2} + O(E^2)$$

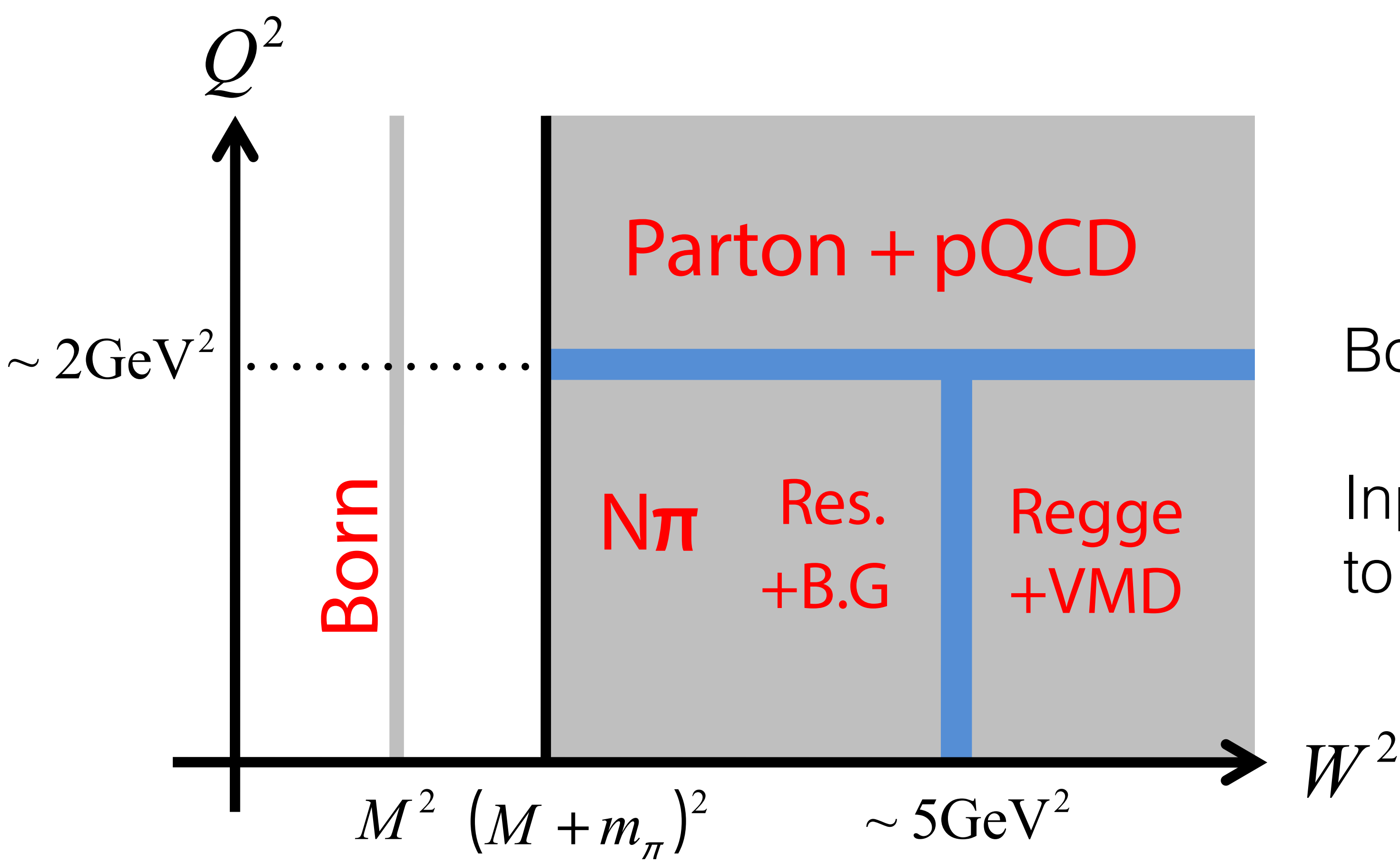
$$\mathrm{Re}\,\Box_{\gamma W}^{odd}(E) = \frac{8\alpha E}{3\pi N M}\int_0^\infty dQ^2 \int_{\nu_{thr}}^\infty \frac{d\nu}{(\nu+q)^3}\left[\mp F_1^{(0)} \mp \left(\frac{3\nu(\nu+q)}{2Q^2} + 1\right)\frac{M}{\nu}F_2^{(0)} + \frac{\nu + 3q}{4\nu}F_3^{(-)}\right] + O(E^3)$$

Input into dispersion integral



Dispersion in energy: $W^2 = M^2 + 2M\nu - Q^2$
scanning hadronic intermediate states

Dispersion in Q²:
scanning dominant physics pictures



Boundaries between regions - approximate

Input in DR related (directly or indirectly) to experimentally accessible data

2.Radiative corrections to nuclear decays: Nuclear structure modification of the free-n RC

C-Y Seng, MG, M J Ramsey-Musolf, arXiv: 1812.03352

Splitting the γW-box into Universal and Nuclear Parts

Evaluate the box on a free neutron

Correction to the (Fermi) decay rate: Δ_R^V **Chien Yeah's talk**

General structure of RC for nuclear decay

$$ft(1+RC) = Ft(1+\delta'_R)(1-\delta_C+\delta_{NS})(1+\Delta_R^V)$$

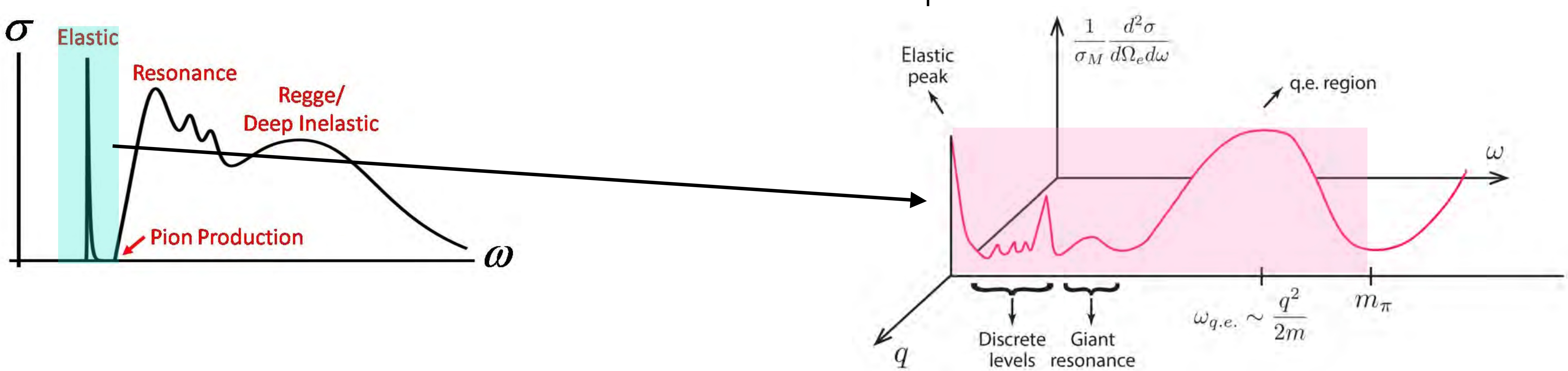
NS correction reflects this extraction of the free box

$$\Box_{\gamma W}^{\text{VA, Nucl.}} = \Box_{\gamma W}^{\text{VA, free n}} + \left[\Box_{\gamma W}^{\text{VA, Nucl.}} - \Box_{\gamma W}^{\text{VA, free n}}\right]$$

Nuclear modification in the lower part of the spectrum

Input in the DR for the universal RC

Input in the DR for the RC on a nucleus



Nuclear γW-box

$$\Box_{\gamma W}^{VA,\ Nucl.} = \frac{\alpha}{N\pi M}\int\limits_0^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}\int\limits_0^\infty d\nu \frac{(\nu+2q)}{\nu(\nu+q)^2}\ F_{3,\,\gamma W}^{(0),\ \mathrm{Nucl.}}(\nu,Q^2)$$

Need to know the full nuclear Green's function
indices k, l count the nucleon d.o.f. in a nucleus

$$T_{\mu\nu}^{\gamma W\ \mathrm{nuc}} \sim \sum_{k,\ell}\langle f|J_\mu^W(k)\,G_{\mathrm{nuc}}\,J_\nu^{\mathrm{EM}}(\ell)|i\rangle$$

Two cases: (A) same active nucleon
(B) two nucleons correlated by G

$$T_{\mu\nu}^{A} = \sum_{k}\langle f|J_\mu^W(k)\,G_{\mathrm{nuc}}\,J_\nu^{\mathrm{EM}}(k)|i\rangle$$

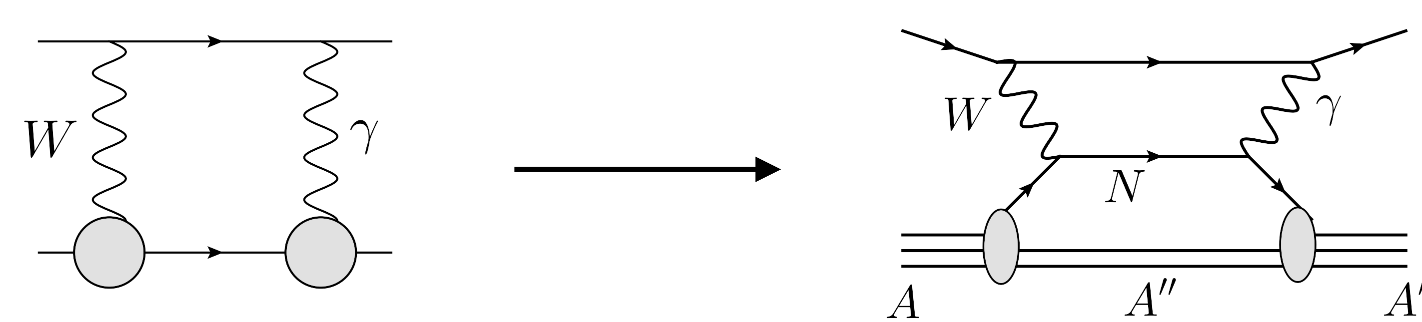
$$T_{\mu\nu}^{B} = \sum_{k\neq\ell}\langle f|_\mu^W(k)\,G_{\mathrm{nuc}}\,J_\nu^{\mathrm{EM}}(\ell)|i\rangle$$

Case (A): on-shell neutron propagating between interaction vertices
Case (B): all two-nucleon contributions (QE 2p2h and nuclear excitations)

Insert on-shell intermediate states:

$$T_{\mu\nu}^{A} \to \sum_{k}\langle f\,|\,J_\mu^W(k)[S_F^N\otimes G_{nuc}^{A''}]J_\nu^{EM}(k)\,|\,i\rangle$$

The elastic nucleon box
is replaced by a single N QE knockout



Universal vs. Nuclear Corrections

universal

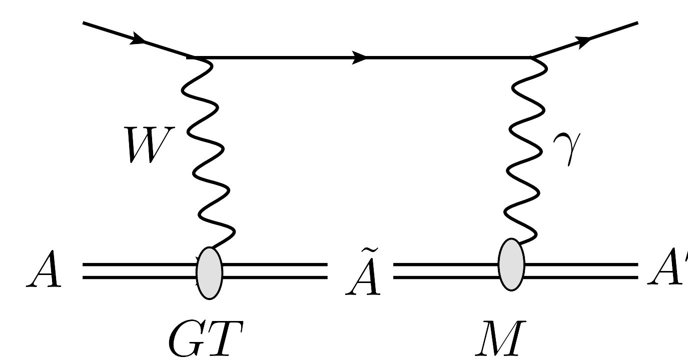
Towner 1994 and ever since: $C_B^{\text{free n}} \to C_B^{\text{Nucl.}} = C_B^{\text{free n}} + [q_S^{(0)} q_A - 1] C_B^{\text{free n}}$

nuclear δ_{NS}

Idea: calculate Gamow-Teller and magnetic nuclear transitions in the shell model;
Insert the single nucleon spin operators —> predict the strength of nuclear transitions
"Quenching of spin operators in nuclei": shell model overestimates those strengths!

Talks by Stefano, Or

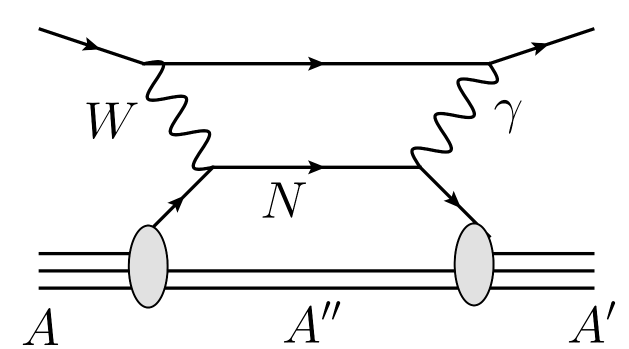
Each vertex is suppressed by 10-15%
Hardy, Towner: just rescale the Born contribution to the γW-box by that quenching,
assume the integral to be the same (nucleon form factors)



Numerically: on average $[q_S^{(0)} q_A - 1] C_B = -0.25$

$$\delta_{NS}^{quenched\,Born} = \frac{\alpha}{\pi}[q_S^{(0)} q_A - 1] C_B \approx -0.055(5)\,\%$$ used since 1998

But from dispersion relation perspective it corresponds
to a contribution of an excited nuclear state,
not to the modified box on a free nucleon!
The correct estimate should base on quasielastic knockout
with an on-shell N + spectator in the intermediate state



Modification of C_B in a nucleus - QE

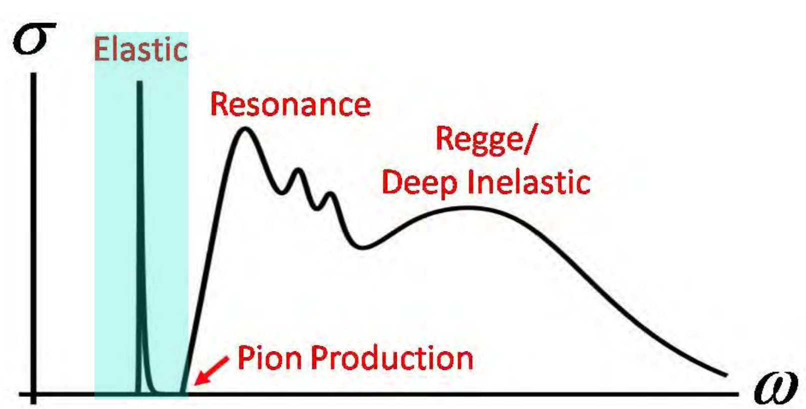
Integral is peaked at low ν, Q^2

$$\Box^{VA,\,Nucl.}_{\gamma W} = \frac{\alpha}{N\pi M}\int_0^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}\int_0^\infty d\nu \frac{(\nu+2q)}{\nu(\nu+q)^2}\, F^{(0),\,\mathrm{Nucl.}}_{3,\,\gamma W}(\nu,Q^2)$$

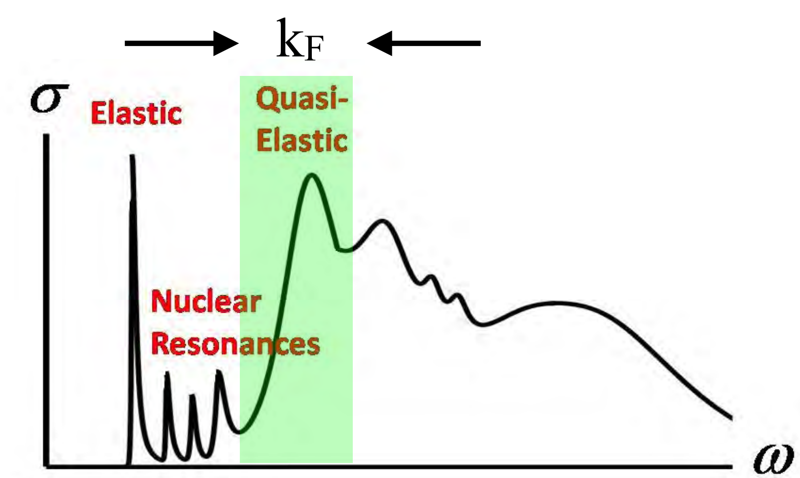
Born on free n:

$$F_3^{(0),\,B} = -\frac{Q^2}{4} G_A G_M^S \delta(2M\nu - Q^2)$$

Reduction for QE:
finite threshold ϵ (binding energy) + Fermi momentum k_F



$\nu = Q^2/2M$



$\nu \geq Q^2/2M + \epsilon$

QE calculation in free Fermi gas model with Pauli blocking
assign a generous 30% model uncertainty

C-Y Seng, MG, M J Ramsey-Musolf, arXiv: 1812.03352

$C_{QE} - C_B = -0.47 \pm 0.14$ compare to the "quenched" estimate $[q_S^{(0)} q_A - 1] C_B = -0.25(6)$

New δ^{QE}_{NS} ~ - 0.11(3)% instead of the previous estimate δ^{q}_{NS} ~-0.058(14)%

QE calculation - effect on Ft values and V_{ud}

Adopting a new estimate of the in-nucleus modification of the free-nucleon Born

Shifts the Ft value according to $\overline{\mathcal{F}t} \to \overline{\mathcal{F}t}(1 + \delta_{NS}^{new} - \delta_{NS}^{old})$

Numerically: $\overline{\mathcal{F}t} = 3072.07(63)s \to [\overline{\mathcal{F}t}]^{\rm new} = 3070.50(63)(98)s$

Will affect the extracted V_{ud} $|V_{ud}|^2 = \frac{2984.432(3)\,\mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$

Compensates for a part of the shift due to a new evaluation of Δ^V_R

$$V_{ud}^{\rm old} = 0.97420(21) \;\to\; |V_{ud}^{\rm new}| = 0.97370(14) \to |V_{ud}^{\rm new,\ QE}| = 0.97395(14)(16)$$

Brings the first row closer to the unitarity (4σ → 2.2σ)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0004 \;\to |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9989 \pm 0.0005$$

and 1 sigma away from the PDG: 0.9994 ± 0.0005

Important messages:
a nuclear contribution may shift by 2 sigma if evaluated with a different method
dispersion relations as a unified tool for treating hadronic and nuclear parts of RC

3.Splitting of the RC into inner and outer

MG, arXiv: 1812.04229

Splitting the RC into “inner” and “outer”

Radiative corrections ~ $\alpha/2\pi$ ~ 10^{-3} Precision goal: ~ 10^{-4}

When does energy dependence matter?
Correction ~ E_e/Λ, with Λ ~ relevant mass (m_e; M_p; M_A)
Maximal E_e ranges from 1 MeV to 10.5 MeV

Electron mass regularizes the IR divergent parts - (E_e/m_e important) - “outer” correction

If Λ of hadronic origin (at least m_π) —> E_e/Λ small, correction ~ 10^{-5} —> negligible
- certainly true for the neutron decay
- hadronic contributions do not distort the spectrum, may only shift it as a whole

However, in nuclei binding energies ~ few MeV — similar to Q-values

A scenario is possible when RC ~ $(\alpha/2\pi)$ x (E_e/Λ^{Nucl}) ~ 10^{-3}

Nuclear structure may distort the electron spectrum

With dispersion relations can be checked straightforwardly!

Nuclear structure distorts the β-spectrum!

Evaluate the E-dependent contribution

$$\mathrm{Re}\,\Box_{\gamma W}^{odd}(E) = \frac{8\alpha E}{3\pi N M}\int_0^\infty dQ^2 \int_{\nu_{thr}}^\infty \frac{d\nu}{(\nu+q)^3}\left[\mp F_1^{(0)} \mp \left(\frac{3\nu(\nu+q)}{2Q^2}+1\right)\frac{M}{\nu}F_2^{(0)} + \frac{\nu+3q}{4\nu}F_3^{(-)}\right] + O(E^3)$$

Estimate with nuclear polarizabilities and size

Photonuclear sum rule: $\alpha_E = \frac{2\alpha}{M}\int_\epsilon^\infty \frac{d\nu}{\nu^3}F_1(\nu,0) = 2\alpha\int_\epsilon^\infty \frac{d\nu}{\nu^2}\frac{\partial}{\partial Q^2}F_2(\nu,0)$

Supplement with the nuclear form factor: $\alpha_E(Q^2) \sim \alpha_E(0)\times e^{-R_{Ch}^2 Q^2/6}$

Radius and polarizability scale with A: $R_{Ch} \sim 1.2\,\mathrm{fm}\,A^{1/3},\ \alpha_E \sim 2.25\times 10^{-3}\,\mathrm{fm}^3\,A^{5/3}$

Dimensional analysis estimate: $\Delta_R(E) = 2\times 10^{-5}\left(\frac{E}{MeV}\right)\frac{A}{N}$

Estimate in Fermi gas model (exact the same as for E-independent)

$$\Delta_R(E) = (2.8 \pm 0.4 \pm 0.8)\times 10^{-4}\left(\frac{E}{MeV}\right)$$

Uncertainty: spread in **ϵ** and k_F, plus 30% on model

Nuclear structure and E-dependent RC

Use the two estimates as upper and lower bound of the effect

$$\Delta_R(E) = (1.6 \pm 1.6) \times 10^{-4} \left(\frac{E}{MeV} \right)$$

Spectrum distortion due to nuclear polarizabilities ~ 0.016 % per MeV

Roughly independent of the nucleus;

The total rate will depend on nucleus: different Q-values!

Correction to Ft values: integrate over spectrum (only total rate measured)

$$\Delta_E^{NS} = \frac{\int_{m_e}^{E_m} dE E p (Q-E)^2 \Delta_R(E)}{\int_{m_e}^{E_m} dE E p (Q-E)^2} \longrightarrow \tilde{\mathcal{F}}t = ft(1+\delta'_R)(1-\delta_C+\delta_{NS}+\Delta_E^{NS})$$

Nuclear structure distorts the β-spectrum!

$$\tilde{\mathcal{F}}t = ft(1+\delta'_R)(1-\delta_C+\delta_{NS}+\Delta_E^{NS})$$

Absolute shift in Ft values $\delta\mathcal{F}t = \mathcal{F}t \times \Delta_E^{NS}$

Decay	Q (MeV)	$\Delta_E^{NS}(10^{-4})$	$\delta\mathcal{F}t(s)$	$\mathcal{F}t(s)$ [3]
^{10}C	1.91	1.5	0.5	3078.0(4.5)
^{14}O	2.83	2.3	0.7	3071.4(3.2)
^{22}Mg	4.12	3.3	1.0	3077.9(7.3)
^{34}Ar	6.06	4.8	1.5	3065.6(8.4)
^{38}Ca	6.61	5.3	1.6	3076.4(7.2)
^{26m}Al	4.23	3.4	1.0	3072.9(1.0)
^{34}Cl	5.49	4.4	1.4	$3070.7^{+1.7}_{-1.8}$
^{38m}K	6.04	4.8	1.5	3071.6(2.0)
^{42}Sc	6.43	5.1	1.6	3072.4(2.3)
^{46}V	7.05	5.6	1.7	3074.1(2.0)
^{50}Mn	7.63	6.1	1.9	3071.2(2.1)
^{54}Co	8.24	6.6	2.0	$3069.8^{+2.4}_{-2.6}$
^{62}Ga	9.18	7.3	2.2	3071.5(6.7)
^{74}Rb	10.42	8.3	2.6	3076(11)

Shift due to Δ_E^{NS}: comparable to precision of 7 best-known decays

$$\overline{\mathcal{F}t} = 3072.07(63)\text{s} \to \overline{\mathcal{F}t} = 3073.6(0.6)(1.5)\text{s}$$

Decay electron polarizes the daughter nucleus

As a result the spectrum is slightly distorted towards the upper end

Positive-definite correction to Ft ~ 0.05%

Previously found: E-independent piece lowers the Ft value by about the same amount

$$\overline{\mathcal{F}t} = 3072.07(63)s \to [\overline{\mathcal{F}t}]^{\text{new}} = 3070.50(63)(98)s$$

Nuclear structure uncertainties might be underestimated

CKM first-row unitarity at a historic low.
Solutions: SM or beyond?

Discrepancy - BSM?

BSM explanation: non-standard CC interactions —> new V,A,S(PS),T(PT) terms

$$H_{S+V} \;=\; (\overline{\psi}_p \psi_n)(C_S \overline{\phi}_e \phi_{\overline{\nu}_e} + C'_S \overline{\phi}_e \gamma_5 \phi_{\overline{\nu}_e}) + (\overline{\psi}_p \gamma_\mu \psi_n) \left[C_V \overline{\phi}_e \gamma_\mu (1+\gamma_5) \phi_{\overline{\nu}_e}\right]$$

Scalar and Tensor interactions: distort the beta decay spectra

Complementarity to LHC searches

Exp. high precision measurement of ^6He spectrum (O. Naviliat-Cuncic, A. Garcia, …)

$$N(E)dE = p_e E(E_m - E)^2 \left[1 + C_1 E + b\frac{m_e}{E}\right]$$

C_1 = 0.00650(**7**) MeV^{-1} - effect of weak magnetism - positive slope
b ~ +- 0.001 - negative slope

Energy-dep. polarizability correction —> C'_1 ~ 0.00020(**20**) MeV^{-1} — at the level 3σ of C_1

Conclusions & Outlook

- The γW-box in the forward dispersion relation framework
- Hadronic and nuclear corrections in a unified framework
- Nuclear structure leaks in the outer correction, distorts the beta decay spectrum
- Better calculations than free Fermi gas should be done
- Nuclear uncertainties shift the emphasis on free neutron decay
- Tensions with CKM unitarity: $\Sigma_{i=d,s,b} |V_{ui}|^2 - 1 = -0.0016(4\text{-}6)$

Nuclear correction δ_{NS}
DR allow to address hadronic and nuclear parts of the calculation on the same footing
The full nuclear correction should be calculated (not just QE) - further test of H&T δ_{NS}

Decay spectra and nuclear polarizabilities
Can contaminate the extraction of Fierz interference from precise spectra!

Further applications
An update of the Gamma-Z correction to weak charges in PVES and atomic PV
Gamma-W box correction to GT rate (nuclear; nucleon - comparison of g_A w. lattice)
Gamma-W box correction to Kl3 decays and V_{us}

Conclusions & Outlook

However… the largest correction to Ft is ISB δ_C non-dispersive

Range from 0.15% to 1.5%

Can its calculation be related to neutron skin calculations for PVES?

Which ingredients are common and which are not?

MESA@Mainz will (?) measure the weak radius of C-12 to <1% (2023 on)

Other nuclei (including symmetric ones) possible in the future

Potentially a strong statement between two fields

We live in a hostile world…

In front of the hotel “Everest” a graffiti first noticed by Leendert (his talk yesterday)

“No CPT gloryless bastards”