SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI

PRISMA

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Nuclear uncertainties in superallowed decays and V_{ud}

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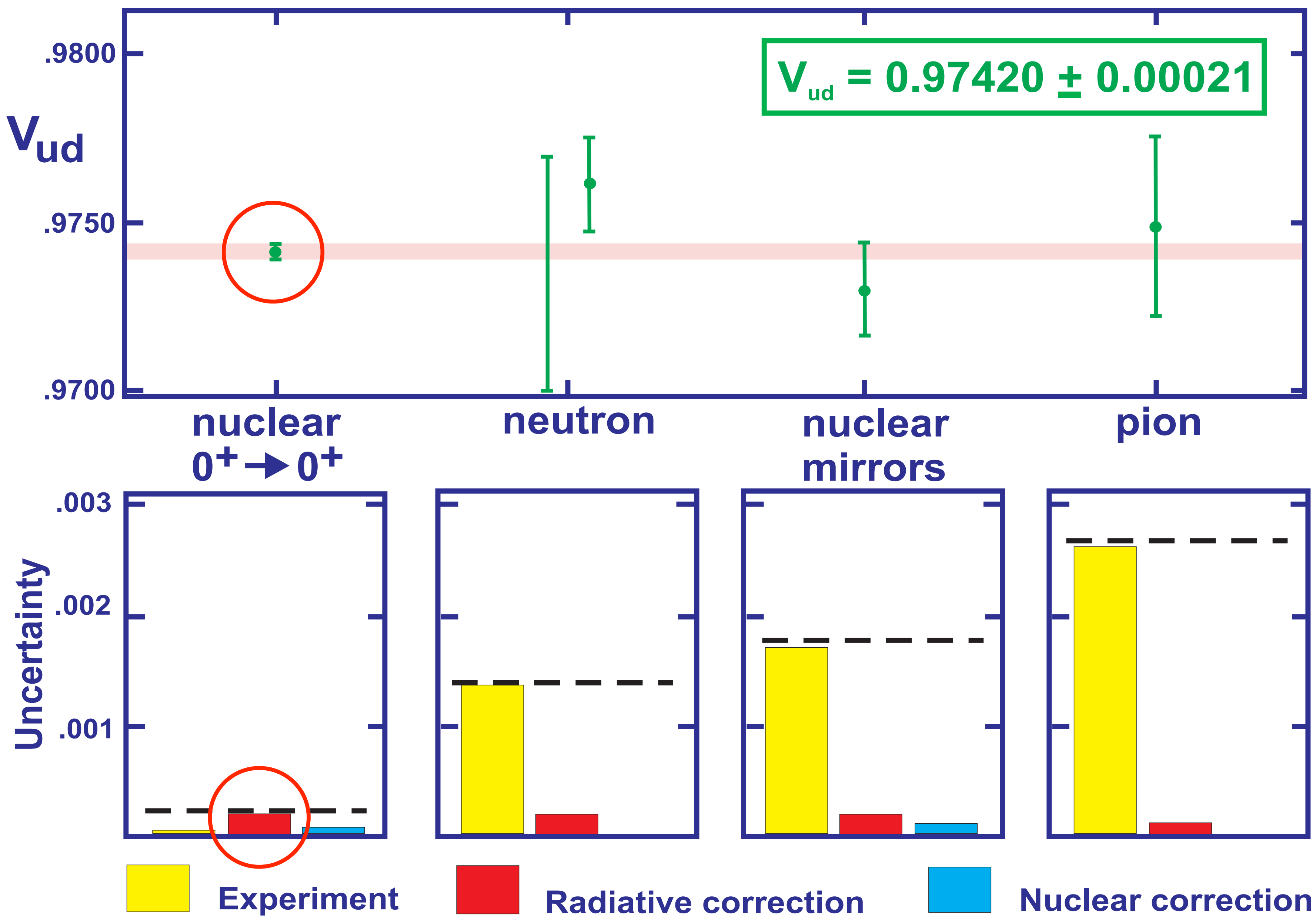
C-Y Seng, MG, H Patel, M J Ramsey-Musolf, arXiv: 1807.10197
C-Y Seng, MG, H Patel, M J Ramsey-Musolf, arXiv: 1811.XXXX
MG, arXiv: 1811.XXXX

November 1, 2018 — Workshop "Beta decay as a Probe of New Physics", ACFI UMass, Amherst, Massachusetts

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

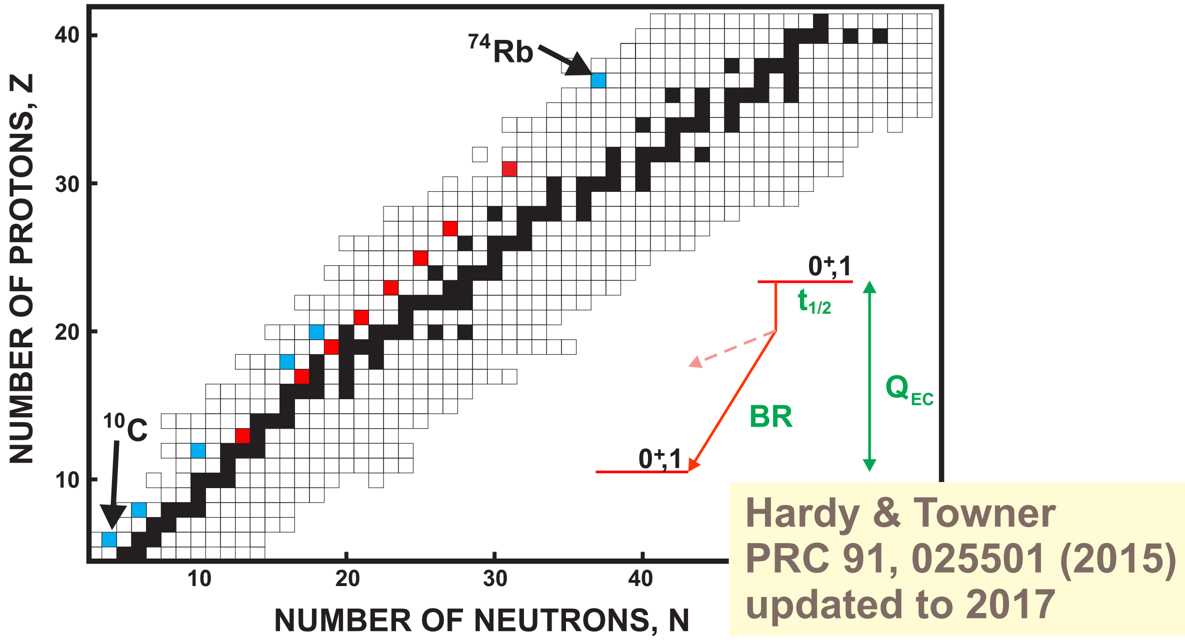
CKM unitarity: V_{ud} the main contributor to the sum and to the uncertainty

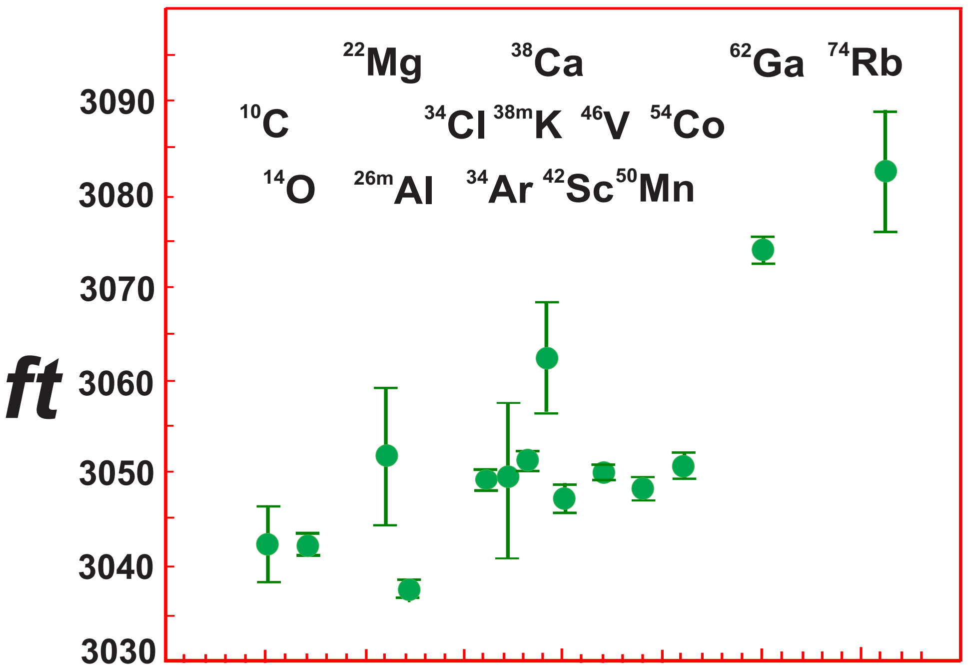
Why are superallowed decays special?

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**





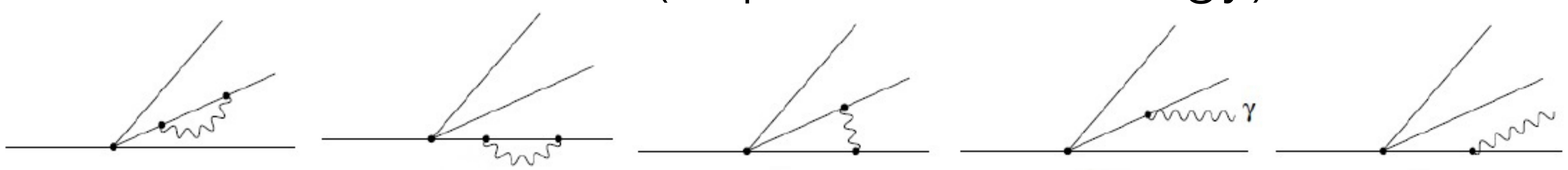
ft values: same within ~2% but not exactly!
Reason: SU(2) slightly broken
a. RC (e.m. interaction does not conserve isospin)
b. Nuclear WF are not SU(2) symmetric (proton and neutron distribution not the same)

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



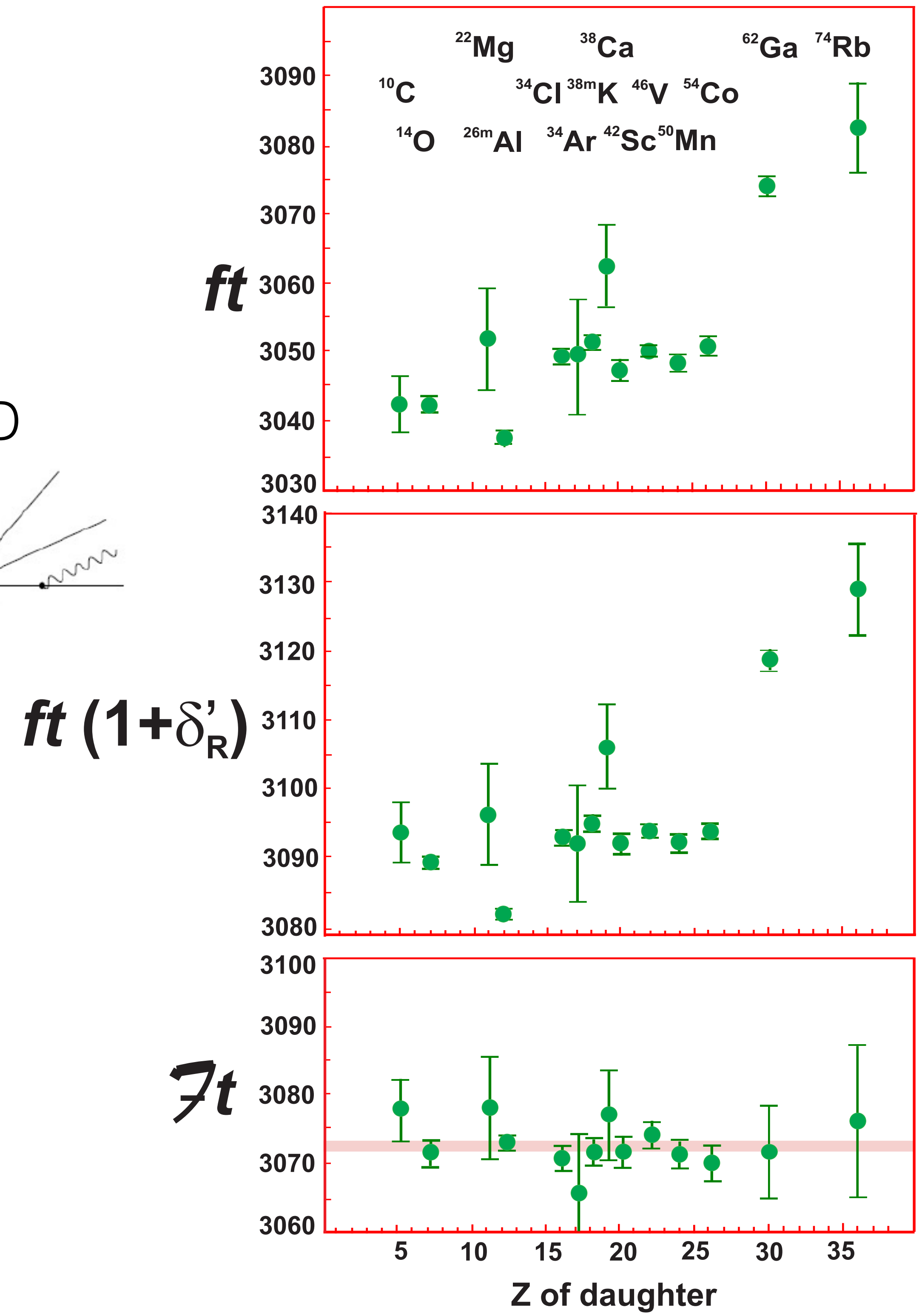
δ_C - SU(2) breaking in the nuclear matrix elements
- mismatch of radial WF in parent-daughter
- mixing of different isospin states

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

General Structure of 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 — 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.

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

C-Y Seng, MG, H Patel, M J Ramsey-Musolf, arXiv: 1811.xxxxx

Caveats in the Ft values

General structure of nuclear and radiative corrections for nuclear decay

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

δ'_R - coulomb distortions: QED + Z of daughter + nuclear size

δ_C - Isospin breaking: correction to the tree-level matrix element of the Fermi op.
implicitly a radiative correction: Coulomb interaction between the protons in a nucleus
shell-model calculation w. Woods-Saxon potential (SM WS)
beyond the scope of this work - but an **independent** check in nuclear models welcome

δ_{NS} - modification of the universal RC due to nuclear environment
Convention: extract the free-nucleon RC explicitly, then correct for each nucleus.
Universal RC calculated by loop techniques or w. DR;
Nuclear modification calculated in SM WS

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

$\Box_{\gamma W}^{\text{VA, free n}} \rightarrow \Delta_R^V$; $\left[\Box_{\gamma W}^{\text{VA, Nucl.}} - \Box_{\gamma W}^{\text{VA, free n}}\right] \rightarrow \delta_{NS}$

If two pieces of one well-defined object are computed in two different frameworks,
the subtraction might be model-dependent!
Desirable to use the same method to compute both - DR is a valid candidate!

Universal vs. Nuclear Corrections

Define the nuclear γW-box per active nucleon

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

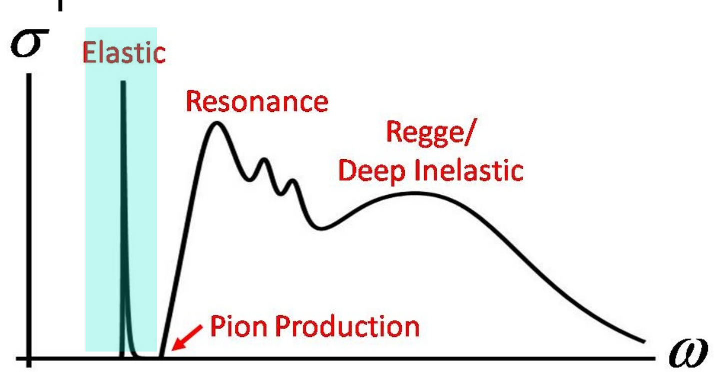
Need the nuclear structure function $F_3^{(0)}$
Where is it different from the free-nucleon $F_3^{(0)}$? - **Everywhere!**

Long distances: LE nuclear structure - excited nuclear states; quasielastic knockout; …
Intermediate distances: widening of N*,Δ-resonances (energy can be shared w. neighbors)
Short distances: shadowing, EMC effect (N of active quarks may depend on kinematics)

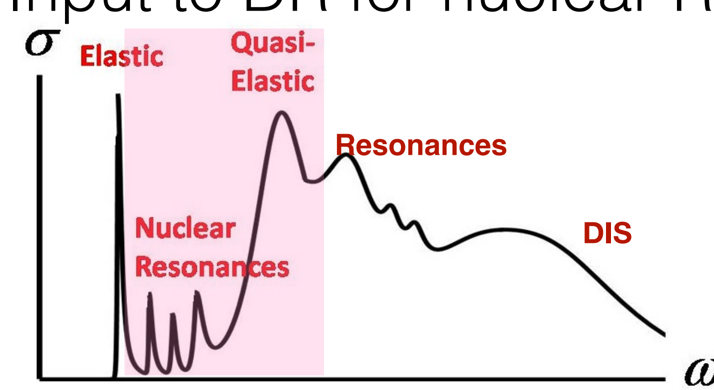
Quite complicated… in the future all these effects **must** be addressed! But:
- The integral has more weight at low energies - HE modifications may be less important;
- N*,Δ-resonances have no impact on the γW-box

To start: consider the long-range part

Input to DR for free-n RC

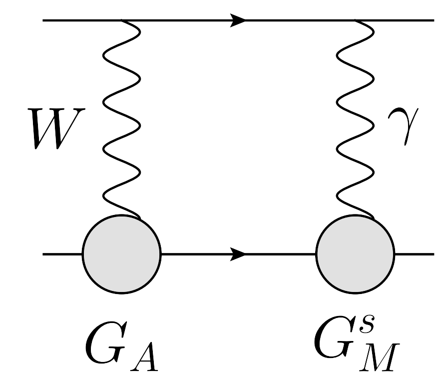


Input to DR for nuclear RC



Universal vs. Nuclear Corrections

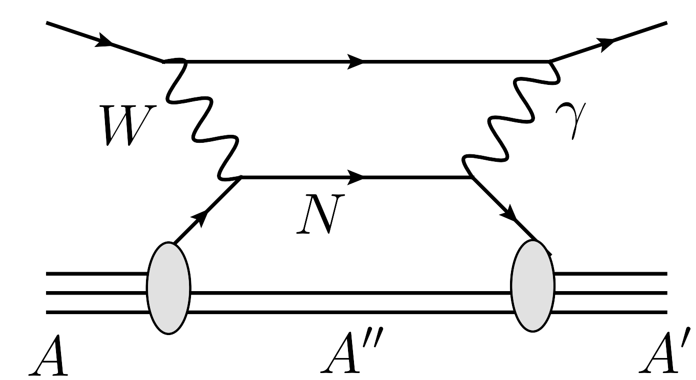
Long-distance content of Δ_R^V - mostly Born contribution



$$\Delta_R^V = \frac{\alpha}{\pi}\left[\text{Short and Intermediate Distance} + \mathbf{C_B}\right]$$

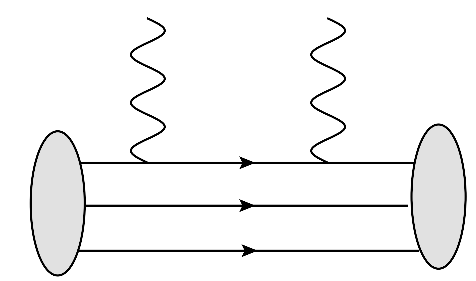
Born uniquely defined: a δ-function in the SF

How is it modified in a nucleus?
Due to binding the nucleon is slightly off-shell and has an initial momentum distribution - a broad QE peak instead of a δ-function

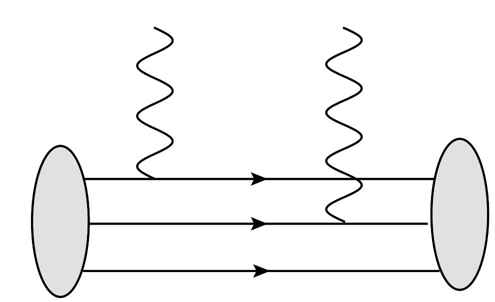


Operating with nucleon d.o.f. — nuclear SF has two contributions:

Coupling to the same nucleon:
Low energy - quasielastic vs. free nucleon Born



Coupling to two different nucleons:
Lowest energies - nuclear excited states,
QE region - 2+ nucleon knockout
SM WS calculations: δ_{NS} ~ -0.3% - 0   Hardy, Towner '15, '18



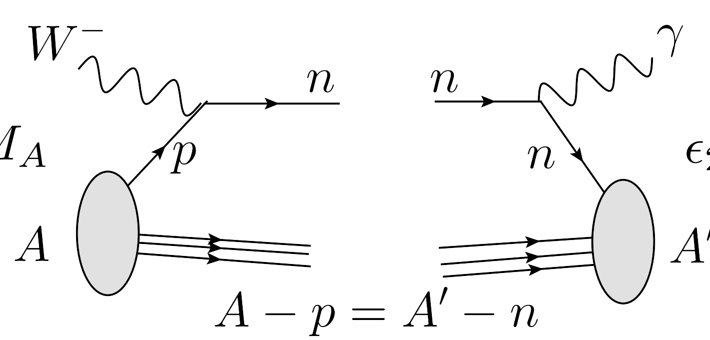
Modification of C_B in a nucleus - QE

$$\square_{\gamma W}^{VA,\,QE} = \frac{\alpha}{\pi M}\int_0^{2\,GeV^2} dQ^2 \int_{\nu_{thr}}^{\nu_\pi} \frac{d\nu(\nu+2q)}{\nu(\nu+q)^2} F_3^{(0)\,QE}(\nu,Q^2) = \frac{\alpha}{2\pi} \mathbf{C_{QE}}$$

Exploratory calculation: disregard fine details, account for main effects
Main features: Fermi momentum and break-up threshold

Problem: mismatch of the initial and final state
Break-up thresholds differ by the Q-value of the decay!
Solution: define an average threshold

$$\epsilon_1 = M_{A-p} + M_n - M_A \qquad \epsilon_2 = M_{A'-n} + M_n - M_A$$



Decay	ϵ_1 (MeV)	ϵ_2 (MeV)	$\bar\epsilon$ (MeV)
$^{10}C \to ^{10}B$	6.70	4.79	5.67
$^{14}O \to ^{14}N$	8.24	5.41	6.68
$^{18}Ne \to ^{18}F$	8.11	4.71	6.18
$^{22}Mg \to ^{22}Na$	10.41	6.28	8.09
$^{26}Si \to ^{26}Al$	11.14	6.30	8.38
$^{30}S \to ^{30}P$	10.64	5.18	7.42
$^{34}Ar \to ^{34}Cl$	11.51	5.44	7.91
$^{38}Ca \to ^{38}K$	11.94	5.33	7.98
$^{42}Ti \to ^{42}Sc$	11.57	4.55	7.25
$^{26m}Al \to ^{26}Mg$	11.09	6.86	8.72
$^{34}Cl \to ^{34}S$	11.42	5.92	8.22
$^{38m}K \to ^{38}Ar$	11.84	5.79	8.28
$^{42}Sc \to ^{42}Ca$	11.48	5.05	7.61
$^{46}V \to ^{46}Ti$	13.19	6.14	9.00
$^{50}Mn \to ^{50}Cr$	13.00	5.37	8.35
$^{54}Co \to ^{54}Fe$	13.38	5.13	8.28
$^{62}Ga \to ^{62}Zn$	12.90	3.72	6.94
$^{66}As \to ^{66}Ge$	12.74	3.16	6.34
$^{70}Br \to ^{70}Se$	13.17	3.20	6.49
$^{74}Rb \to ^{74}Kr$	13.85	3.44	6.90

Effective removal energies - all in a small range

$$\bar\epsilon = 7.5 \pm 1.5 MeV$$

Fermi momenta also not too different for all A

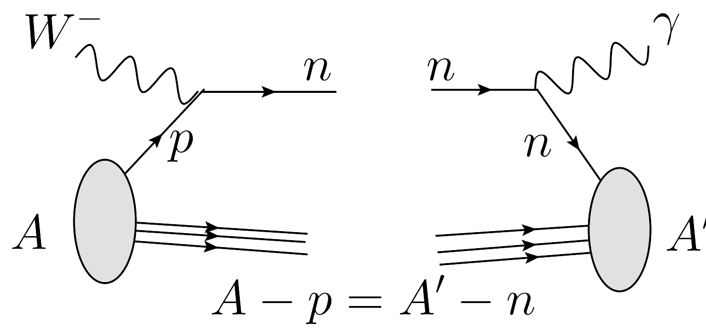
$$k_F(A=10) = 228\,\mathrm{MeV}, \quad k_F(A=74) = 245\,\mathrm{MeV}$$

Modification of C_B in a nucleus - QE

A simple calculation of a QE cross section:
nucleon momentum distribution $\phi_A{}^p \simeq \phi_{A'}{}^n$

$$\int \frac{d^3\vec{k}}{(2\pi)^3}|\phi(k)|^2 = 1$$

$$|A\rangle = \sqrt{2E_A}\sum_{p\in A}\int \frac{d^3\vec{k}\,\phi_A^p(k)\,|p(\vec{k}), A-p(-\vec{k})\rangle}{(2\pi)^3\sqrt{2E_{A-1}\,2E_n}}$$



$$|A'\rangle = \sqrt{2E_{A'}}\sum_{n\in A'}\int \frac{d^3\vec{k}\,\phi_{A'}^n(k)\,|n(\vec{k}), A'-n(-\vec{k})\rangle}{(2\pi)^3\sqrt{2E_{A-1}\,2E_n}}$$

Free Fermi gas model $\quad \frac{1}{(2\pi)^3}|\phi(k)|^2 = \frac{3}{4\pi k_F^3}\theta(k_F - |\vec{k}|)$

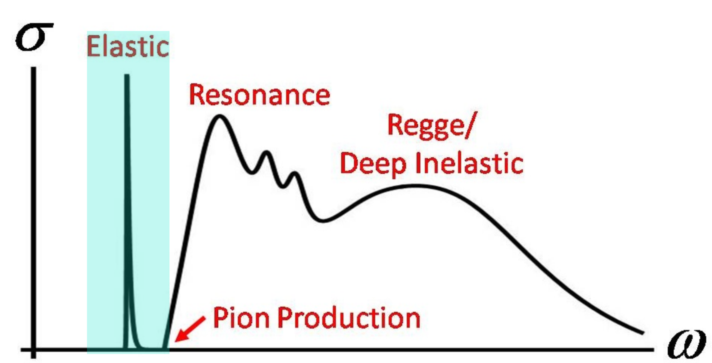
Pauli blocking $\quad F_P(|\vec{q}|, k_F) = \frac{3|\vec{q}|}{4k_F}\left[1 - \frac{\vec{q}^2}{12k_F^2}\right] \quad \text{for } |\vec{q}| \le 2k_F$

Result of the calculation: Born suppressed by ~ factor 2 $\quad \mathbf{C_{QE} - C_B = -0.45 \pm 0.04}$

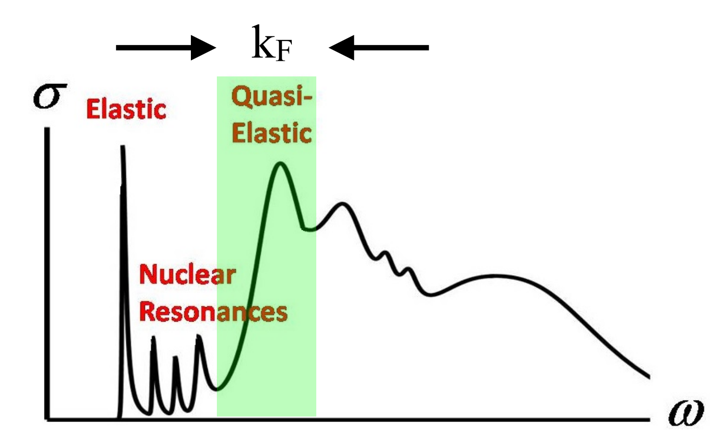
Reason for suppression:

integrand ~ $\frac{F_3^{\gamma W}(0)}{\nu^2}$

QE: finite threshold;
Bulk of QE shifted by k_F



$\nu = Q^2/2M$



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

Universal vs. Nuclear Corrections

Compare to existing estimate!
Towner 1994 and ever since:

universal

$$C_B^{\text{free n}} \to C_B^{\text{Nucl.}} = C_B^{\text{free n}} + [q_S^{(0)} q_A - 1] C_B^{\text{free n}}$$

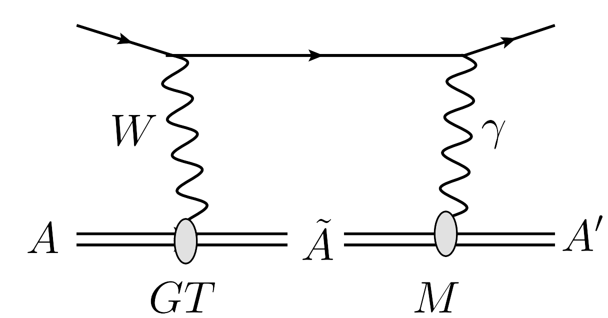
nuclear δ_{NS}

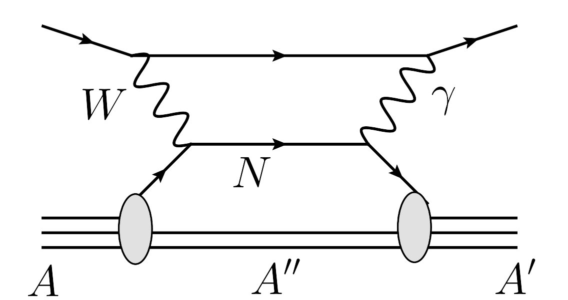
Idea: calculate Gamow-Teller and magnetic nuclear transitions in the shell model;
Insert the single nucleon spin operators —> predict the strength of nuclear transitions
"Quenching of spin operators in nuclei": shell model overestimates those strengths!

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

δ^{qB}_{NS} ~ - 0.055(5)% used in all reviews 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

$C_{QE} - C_B = -0.45 \pm 0.04.$ compare to the H&T estimate $[q_S^{(0)} q_A - 1] C_B = -0.25$

New δ^{QE}_{NS} ~ - 0.10(1)% instead of the previous estimate δ^{q}_{NS} ~-0.055(5)%

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

Numerically: $\mathcal{F}t = 3072.07(63)s \to [\mathcal{F}t]^{\text{new}} = 3070.65(63)(28)s$

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

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

$$V_{ud}^{\text{old}} = 0.97420(21) \;\to\; V_{ud}^{\text{new}} = 0.97370(14) \to V_{ud}^{\text{new, QE}} = 0.97392(14)(04)$$

Brings the first row a little closer to the unitarity (4σ ➞ 3σ)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0004 \quad \to |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9988 \pm 0.0004$$

Important message:
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: 1811.xxxxx**

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 ~ $(\alpha/2\pi) \times (E_e/\Lambda^{Nucl})$ ~ 10^{-3}

Nuclear structure may distort the electron spectrum

With dispersion relations can be checked straightforwardly!

Nuclear structure and E-dependent RC

With DR: can include linear terms in energy
Even and odd powers of energy - leading terms

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

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

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

Nuclear structure and E-dependent RC

E-dependent correction: estimate in Fermi gas model (similar to E-independent)

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

Uncertainty: spread in ϵ and k_F

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 comparable with the precision of the 7 best-known decays

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

Decay electron polarizes the daughter nucleus

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

Changes the rate at 0.05% level

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

$$\mathcal{F}t = 3072.07(63)s \rightarrow [\mathcal{F}t]^{\text{new}} = 3070.65(63)(28)s$$

The two effects tend to cancel each other; a good problem for hard-core nuclear theorists!

RC to β-decay from dispersion relations: Summary

All three sources of possible model dependence addressed with DR

At each step a considerable shift beyond the previously assumed precision is observed

Universal correction: the biggest shift (2.5 σ) but the uncertainty reduced

Matching hadronic and nuclear corrections: shift (- 2σ) to the Ft value

Nuclear polarizabilities distort the β-spectrum, split inner-outer RC ambiguous:
shift ~ (+2σ) to the Ft value

Net effect: (4σ) deficit for the first-row unitarity $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0004$

Some increase in the nuclear uncertainty is likely

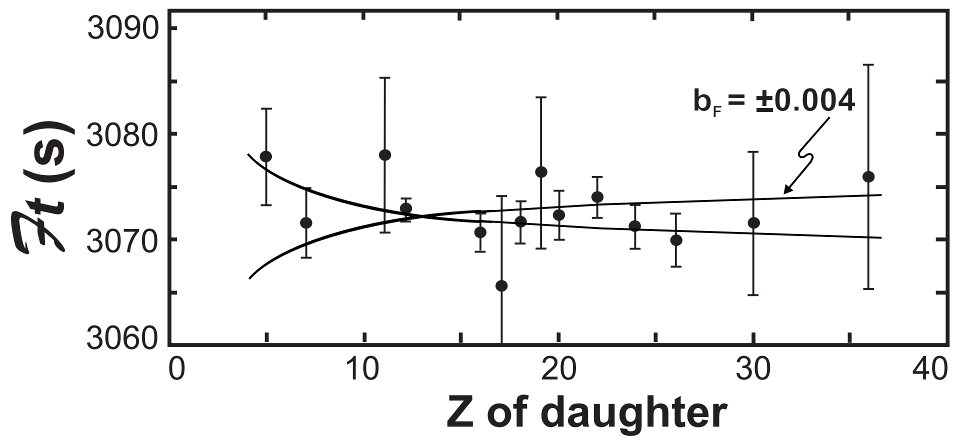
CKM first-row unitarity at a historic low.
Solutions: SM or beyond?

Discrepancy - BSM?

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

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

Fierz interference: distort the spectrum, affect Ft values $b_F \dfrac{m_e}{E_e}$



$$\frac{C_S}{C_V} = -\frac{b_F}{2} = +0.0014 \pm 0.0013$$

Exp. plans: high precision measurement of ^{6}He spectrum (A. Garcia et al., U. Washington)

Complementarity to LHC searches (Gonzalez Alonso et al., arXiv: 1803.08732)

Discrepancy - SM?

Hadronic correction Δ_R^V
Neutrino data at low Q^2 are not precise
upcoming DUNE experiment @ Fermilab may provide better data for F_3
- can check the parametrization of F_3^{WW} directly

Isospin rotation needs to be tested separately:
axial Z-N coupling is a pure isovector —> $4F_3^{(0)} \approx F^p_{3,\gamma Z} - F^n_{3,\gamma Z} \approx 2F^p_{3,\gamma Z} - F^d_{3,\gamma Z}$

Update axial γZ-box —> a change in $F_3^{\gamma Z}$ —> a shift in weak charge (seems small)

Moments $M_3^{(0)}(N,Q^2)$ from lattice?

Nuclear correction δ_{NS}
DR allow to address hadronic and nuclear parts of the calculation on the same footing

But data will not guarantee the needed precision —> use nuclear model input

The trouble is with V_{us}
Discrepancy in V_{us} from Kl3 and Kl2 decays

Could be due to RC? γW-box?

$$|V_{ud}|^2 + |V_{us}^{K\ell 2}|^2 + |V_{ub}|^2 = 0.9979(5)$$

$$\text{PDG}: \ |V_{ud}|^2 + |\overline{V_{us}}|^2 + |V_{ub}|^2 = 0.9984(4)$$

$$|V_{ud}|^2 + |V_{us}^{K\ell 3}|^2 + |V_{ub}|^2 = 0.9988(5)$$