Status of V_{ud} anno 2022

Leendert Hayen

ELECTRO2022, October 24 2022

NC State & TUNL, USA

Contents

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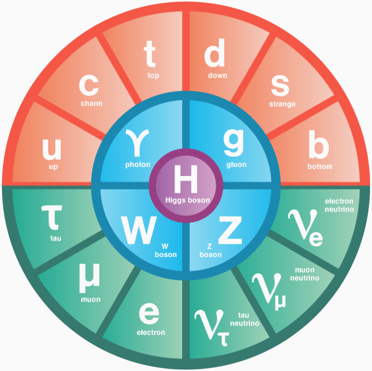
Introduction: Standard Model

'Simple' gauge groups:
$SU(3)_c \times SU(2)_L \times U(1)_Y$



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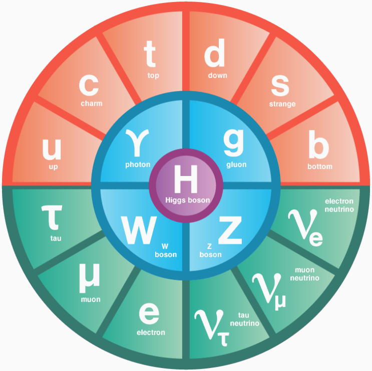

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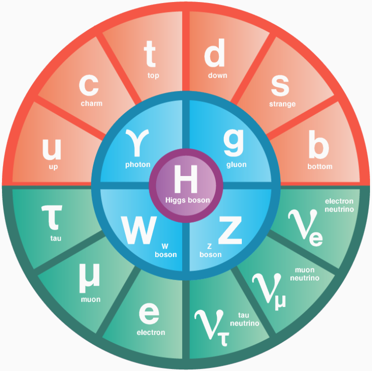

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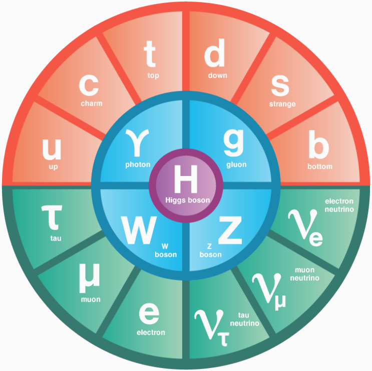
Open questions: dark matter, gravity, neutrino masses, ...



CKM unitarity

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_w = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_m$$

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Unitarity requires

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

Violations are sensitive to **TeV scale** new physics!

CKM unitarity: Current status

Signs of non-unitarity at few σ level...

Disagreement between $Kl2$ and $Kl3$ $|V_{us}|$ 'Cabibbo angle anomaly'

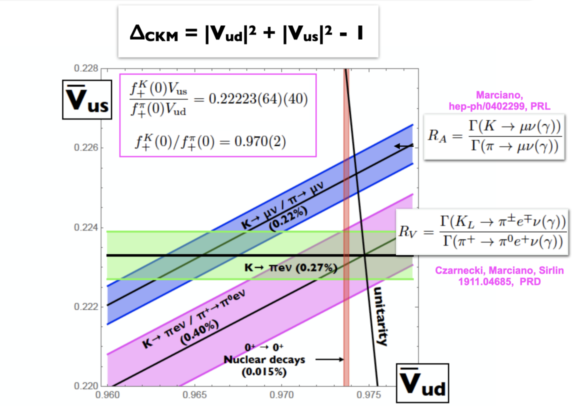
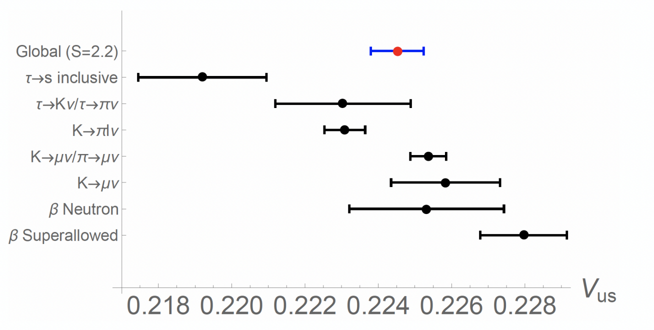


Figure by Vincenzo Cirigliano, DND 2020

CKM unitarity: Cabibbo Angle Anomaly

Signs of non-unitarity at several σ (Falkowski CKM2021)



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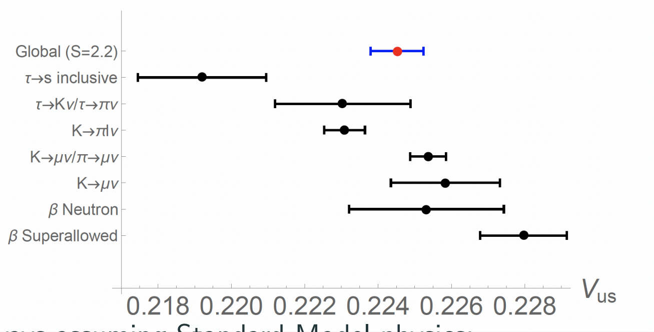
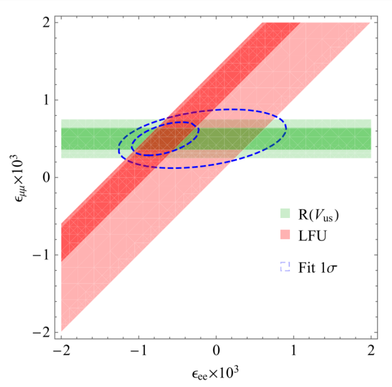
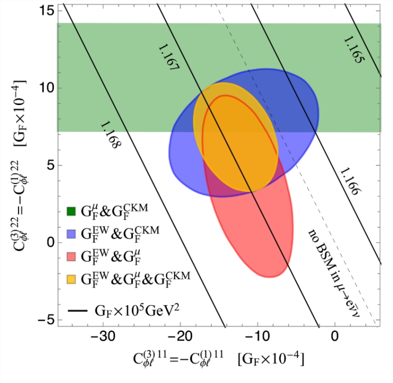


Takeaways assuming Standard Model physics:

- Most precise V_{ud} & V_{us} not consistent with unitarity
- Significant internal inconsistencies within V_{us}
- Taken at face value $\sim 3\sigma$ for new physics

Interesting channel for LFU & SMEFT BSM searches





Crivellin et al., PRL 125 (2020) 111801; PRL 127 (2021) 071801

CKM unitarity: V_{ud}

Let's break it down: How to obtain V_{ud}?

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Semi-leptonic up-down decay rate

$$\Gamma \propto G_F^2 |V_{ud}|^2 (1 + RC) |\langle O_{\text{hadr}} \rangle|^2 \times \text{phase space}$$

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Things you need to know

- G_F (μ lifetime)
- Radiative corrections
- Hadronic theory
- For each β transition: $t_{1/2}, Q_\beta$, BR, (GT/F mixing)

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Things you need to know

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Everything to $\lesssim 0.01\%$! **Recent changes**

CKM unitarity: V_{ud} precision

Nuclear sandbox $\rightarrow$ make hadronic theory easy

- Pion
- Neutron
- Superallowed $0^+ \rightarrow 0^+$
- $T = 1/2$ mirrors

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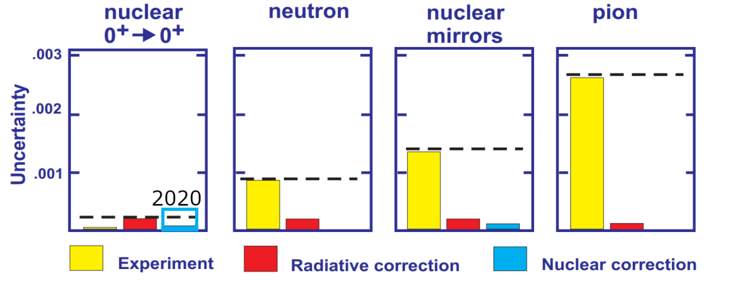

$\pi^+ \rightarrow \pi^0 e^+ \nu_e$ very hard (BR $\sim 10^{-8}$), SA new nuclear corrections!

Modified from J. Hardy, UMass Amherst May 2019

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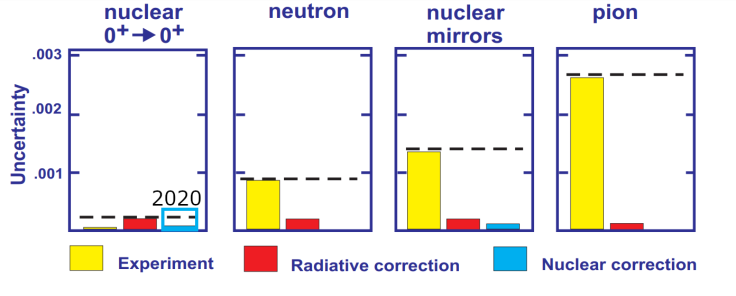

Mirror systems offer enhancement & complementary theory check

Modified from J. Hardy, UMass Amherst May 2019

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Nucleus: Superallowed $0^+ \to 0^+$

For pure vector transitions, can construct

$$\mathcal{F}t \equiv ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) = \frac{K}{2|V_{ud}|^2 G_F^2 (1 + \Delta_R^V)}$$

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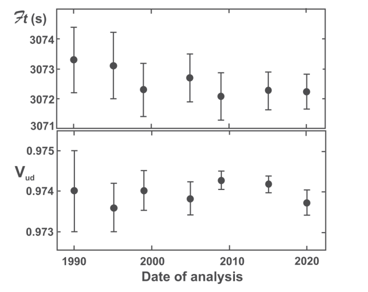
Historically very stable

$\overline{\mathcal{F}t} = 3072.24(57)_{\mathrm{stat}}(36)_{\delta'_R}(173)_{\delta_{NS}}\ s$

Uncertainty limited by theory, likely to continue



"TH20": Hardy & Towner PRC 102 (2020) 045501

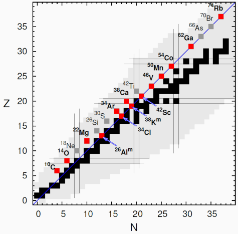
Nucleus: Superallowed $0^+ \to 0^+$

Pure Fermi transitions, $M_F = \sqrt{2}$

$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

Several small $\mathcal{O}(0.1\% - 2.5\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.03\%$



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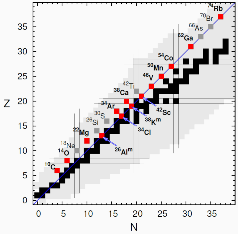
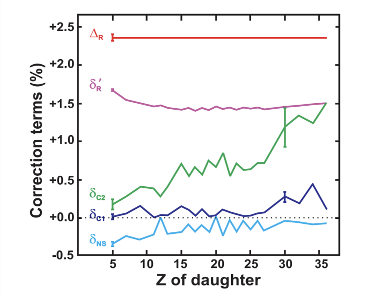
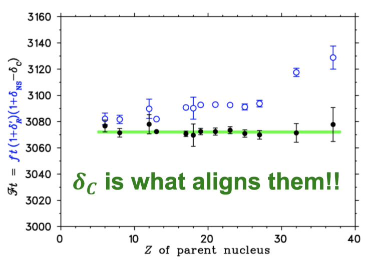


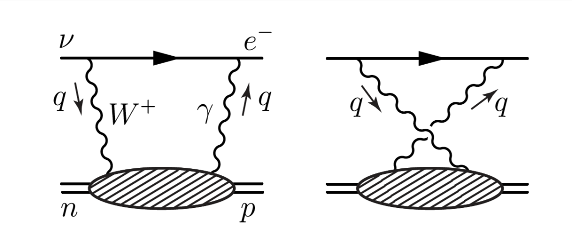




All corrections **recently changed** or **under scrutiny**

Recent changes: Δ_R^V

The culprit for Δ_R^V



Specifically, axial-vector contribution $\to$ symmetries don't save you & QCD at intermediate effects

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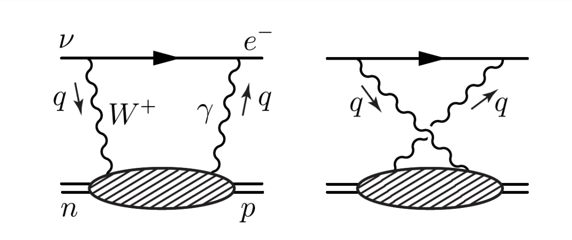


Specifically, axial-vector contribution $\rightarrow$ symmetries don't save you & QCD at intermediate effects

$+50$ years of research to improve it

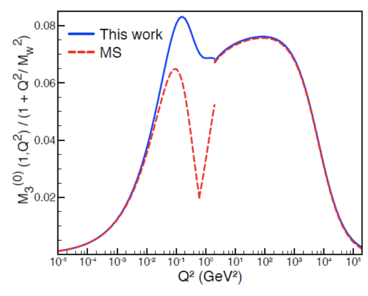
Recent changes: Δ_R^V

Recent breakthrough using dispersion relations

2006: Marciano & Sirlin $\Delta_R^V = 0.02361(38)$, but heuristic uncertainty from 'intermediate' energy scale

2018: Seng, Gorchtein, Patel, Ramsey-Musolf $\Delta_R^V = 0.02467(22)$ 4 σ shift

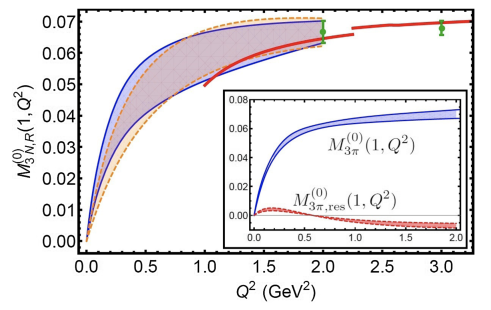
Beginning of our CKM debacle!



Seng, Gorchtein, Ramsey-Musolf PRD 100 (2019) 013001

Recent changes: Δ_R^V & role of LQCD

Lattice QCD starts being used for γW, but QCD + QED very hard for baryons



Seng *et al.*, PRD 101 (2020) 111301

Use pions & relate to nucleon $\rightarrow \Delta_R^V = 0.02477(24)$ (See Feng)

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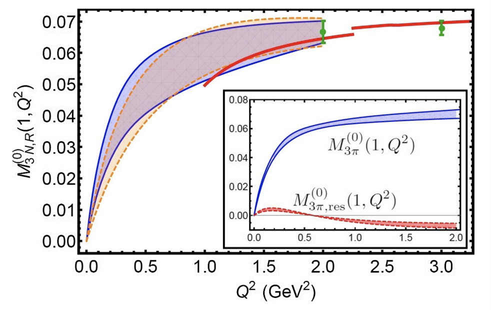

Seng *et al.*, PRD 101 (2020) 111301

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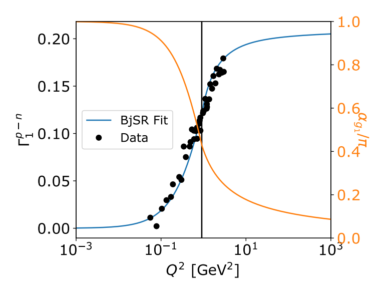
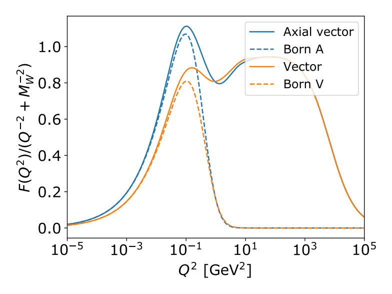
Efforts for $\Delta_R^A + \Delta_R^V$ from χPT & LQCD (See Walker-Loud)

Recent changes: axial RC

First $\mathcal{O}(\alpha)$ calculation of Δ_R^A, dispersion relation allows use of Bjorken sum rule data





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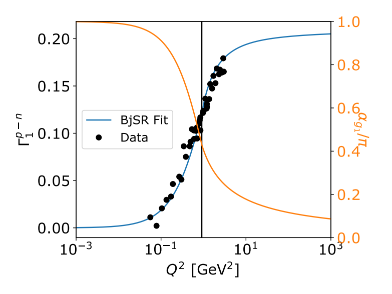
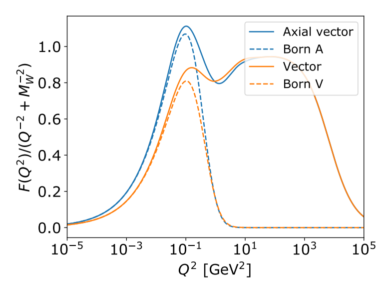




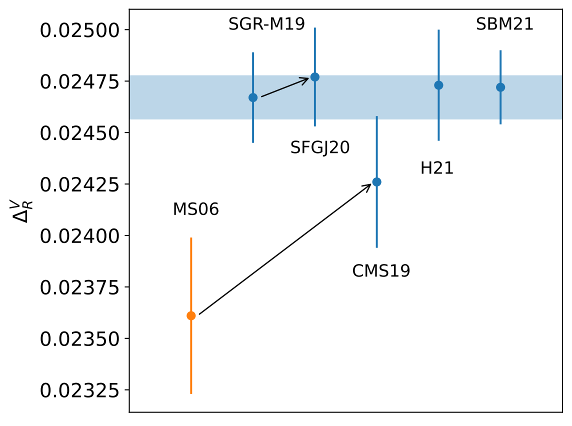
Use analytical continuation in non-perturbative regime constrained by data

$$\Delta_R^V = 0.02473(27) \qquad \Delta_R^A = 0.02532(22)$$

LH, PRD 103 113001; Seng, Particles 2021, 397; Gorchtein & Seng, JHEP 10 53

Recent changes: Δ_R^V

Number of new calculations performed



Now good convergence: uncertainty halved but about 3σ shift

Recent changes: δ_{NS}

Free nucleon Δ_R^V converged, but nucleon response in γW box is modified in nuclear medium $\square_{\gamma W}^{\text{free n}} \to \square_{\gamma W}^{\mathrm{nucl}}$

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Traditionally separated into 1-nucleon γW (A) and 2-nucleon (B)

$$\delta_{NS} = \delta_{NS}^{A} + \delta_{NS}^{B}$$

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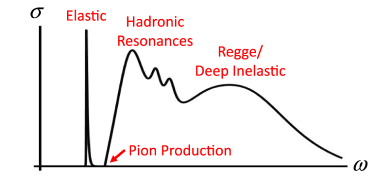
$$\delta_{NS} = \delta_{NS}^{A} + \delta_{NS}^{B}$$

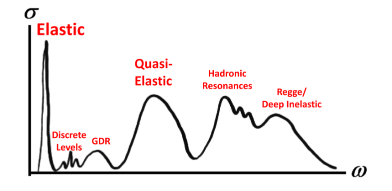
Significant changes to δ_{NS}^{A} due to quasi-elastic processes

Additionally, δ_{NS}^{B} needs attention (see below)

Recent changes: δ_{NS}^{A}

Towner (1992) quenched Born amplitudes like Gamow-Teller, **but**





SGR-M19 argue δ_{NS}^{A} dominated by quasi-elastic processes

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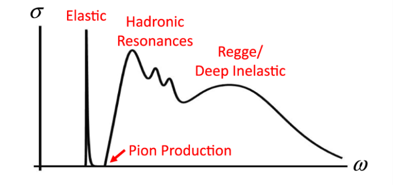
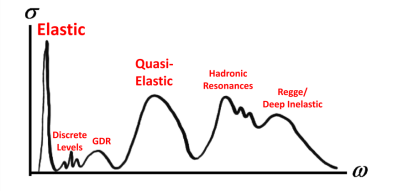
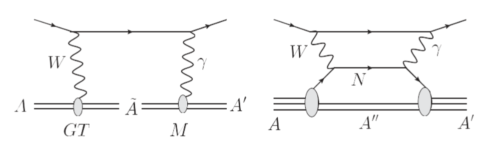




SGR-M19 argue δ_{NS}^{A} dominated by quasi-elastic processes

$$\begin{aligned}\delta_{NS}^{A} =& \frac{\alpha}{\pi}[q_A q_S^{(0)} - 1] C_{\text{Born}}^{\text{free}} \\ \longrightarrow & \frac{\alpha}{\pi}[-0.47 \pm 0.14]^{\text{QE}}\end{aligned}$$



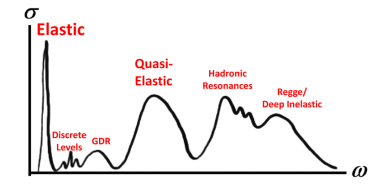
(a) (b)

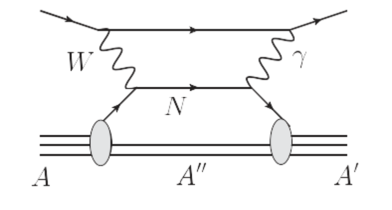
Estimated using free Fermi gas, needs ab initio calculation

Towner, Nucl Phys A 540 478; Seng et al., PRD 100 013001

Recent changes: δ_{NS}^{A}

Gorchtein identified additional issue: typically δ_R' and Δ_R^V can be separated because $E_e/\Lambda_{QCD} \ll 1$, but in nuclei $\Lambda \sim$ MeV





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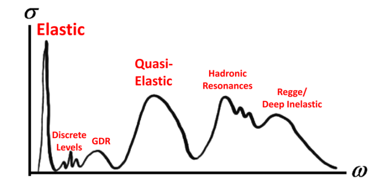
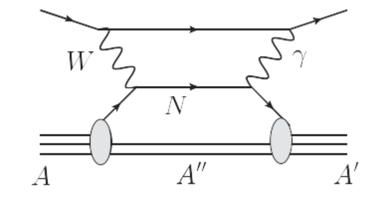




Nucleus can be polarized, results in spectral changes

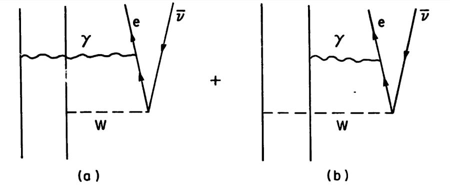
$$\delta_{NS}^{A}(E) \sim (1.6 \pm 1.6) \times 10^{-4} \left(\frac{E}{\mathrm{MeV}}\right)$$

Needs more sophisticated modeling, accessible in spectrum measurements! **Current $\overline{\mathcal{F}t}$ bottleneck!!** (correlated uncertainty)

Gorchtein PRL 123 042503

Needs scrutiny: δ_{NS}^{B}

Not updated since Towner (1992), only non-relativistic shell-model calculations



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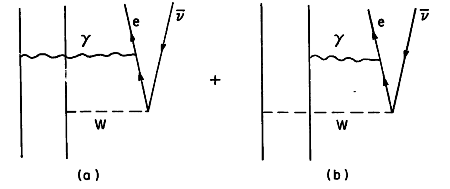

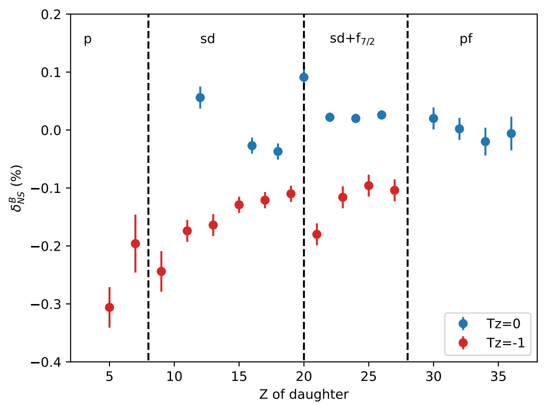

For ^{10}C now $\delta_{NS}^{B} > 3\sigma_{\mathrm{exp}}$, crucial isotope for b_F & $|V_{ud}|$

Prime χPT ab initio candidate!

Needs scrutiny: δ_C

Proton $\neq$ neutron inside nucleus $\rightarrow M_F^2 = 2(1 - \delta_C)$

1. Configuration interaction difference initial $\leftrightarrow$ final
2. Different radial wave function (Coulomb)

$$\delta_C = \delta_{C1} + \delta_{C2}$$

Needs scrutiny: δ_C

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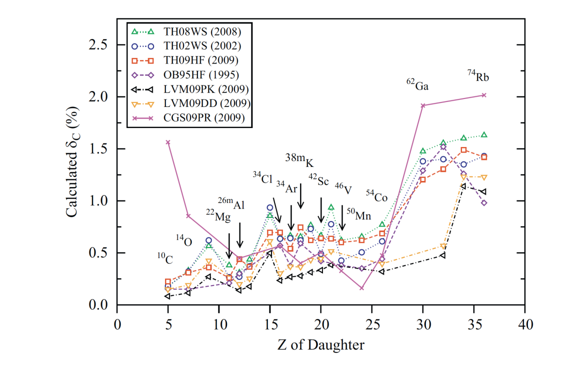


Grinyer et al., NIMA 622 (2010) 236

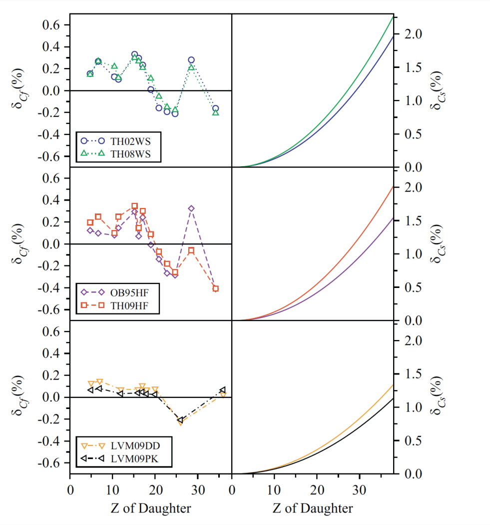
Main effect should go $\propto Z^2$

Despite difference in magnitude, shell structure captured quite well by most

Write

$$\delta_C = aZ^2 + \delta_{Cf}$$

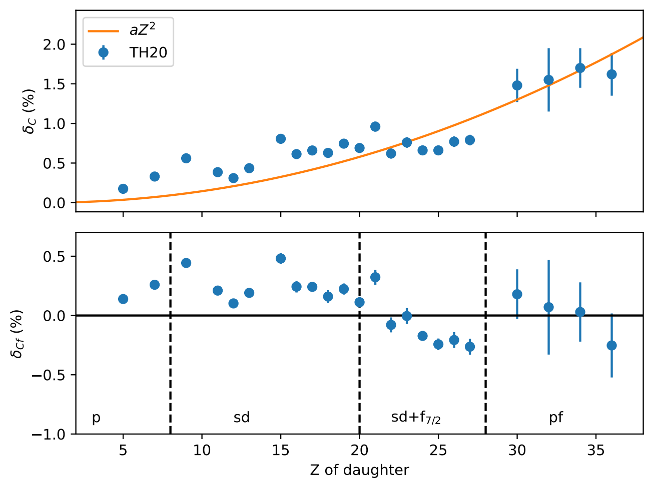
to isolate shell structure



Grinyer et al., NIMA 622 (2010) 236

Needs scrutiny: δ_C

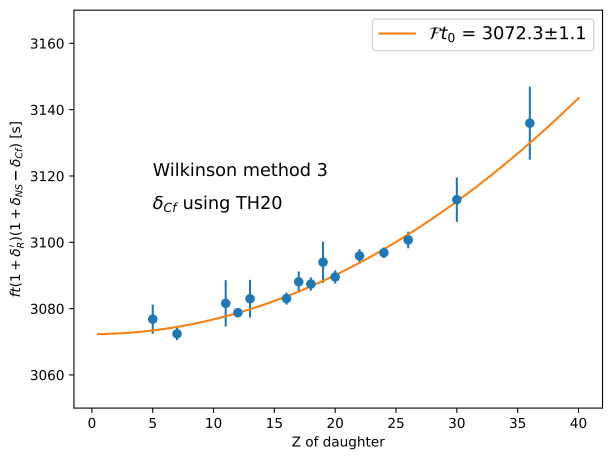
Look at shell structure of TH20 calculations, unweighted fit



mainly shell effects for low masses → test for ab initio?

Needs scrutiny: δ_C

Can use Wilkinson's phenomenological extraction as a 'cross-check'



Consistent with $\overline{\mathcal{F}t}$ for TH20, but insensitive to common shift

Grinyer et al., NIMA 622 (2010) 236

Current status: δ_R'

Outer RC complete at $\mathcal{O}(\alpha^2 Z)$, estimated at $\mathcal{O}(\alpha^3 Z^2)$, unknown at higher order.

Current status: δ'_R

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Following TH15, all isotopes have correlated δ'_R uncertainty of $1/3$ of $\mathcal{O}(\alpha^3 Z^2)$ effect.

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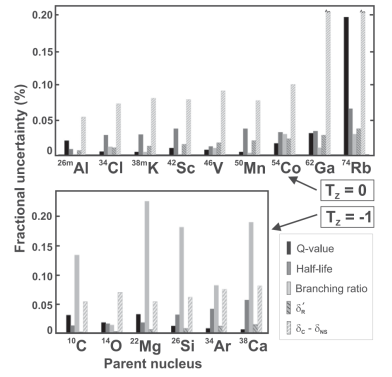
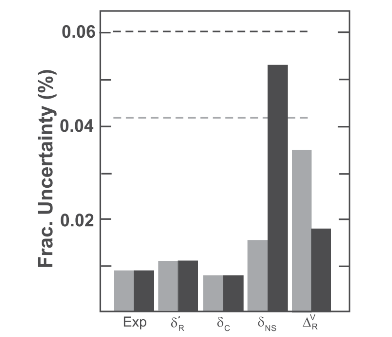
Following TH15, all isotopes have correlated δ'_R uncertainty of $1/3$ of $\mathcal{O}(\alpha^3 Z^2)$ effect.

Contributes 0.36 s uncertainty to $\mathcal{F}t$. Not ideal, but likely not critical for a while

Superallowed summary

Experimentally, $T_z = -1$ limited by BR





Theory, δ_{NS} and δ_C need substantial progress (See Holt)

Hardy & Towner PRC 102 (2020) 045501

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The neutron

Neutron β decay is *theoretically* cleanest baryonic system

$$|V_{ud}|^2 = \frac{5098.7s}{\tau_n(g_V^2 + 3g_A^2)(1 + RC)}$$

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- Q_β ✓
- Branching ratio ✓
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- τ_n

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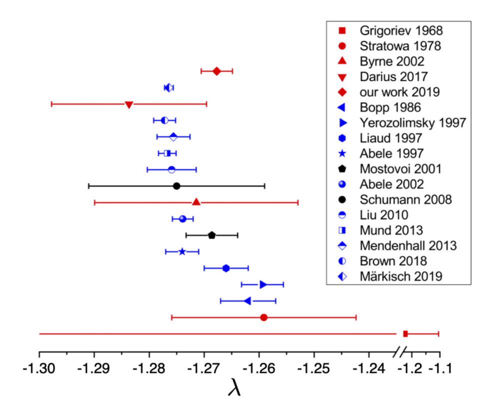
The neutron: λ

Neutron is cleanest probe of $\lambda = g_A/g_V$, but evolution

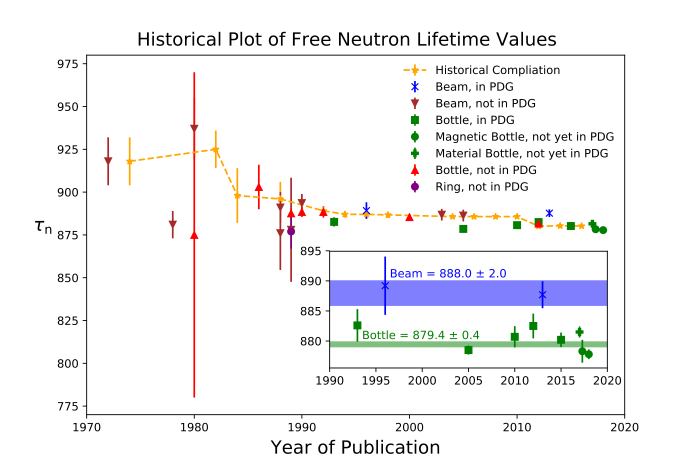


Tension between PERKEO3 and aSPECT, both 2020

PRC 101 (2020) 055506

The neutron: τ_n

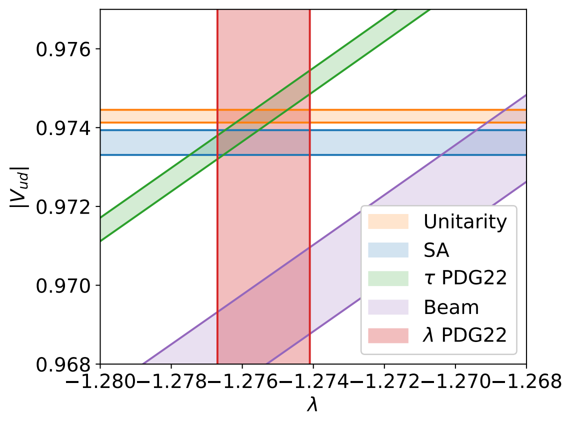
Evolution of τ_n, essential in BBN



Bottle: Count survivors; Beam: Count decay products (See Fertl)

The neutron status

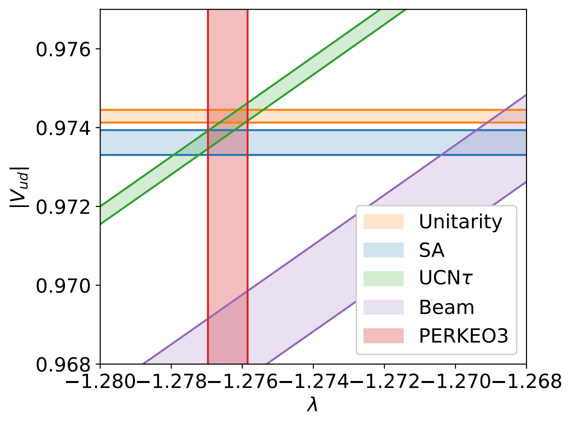
Using PDG22 τ_n [878.4(5)s] and λ [$-1.2754(13)$]



3 times less precise than SA ($S = 1.8$ for τ_n; $S = 2.7$ for λ)

The neutron status

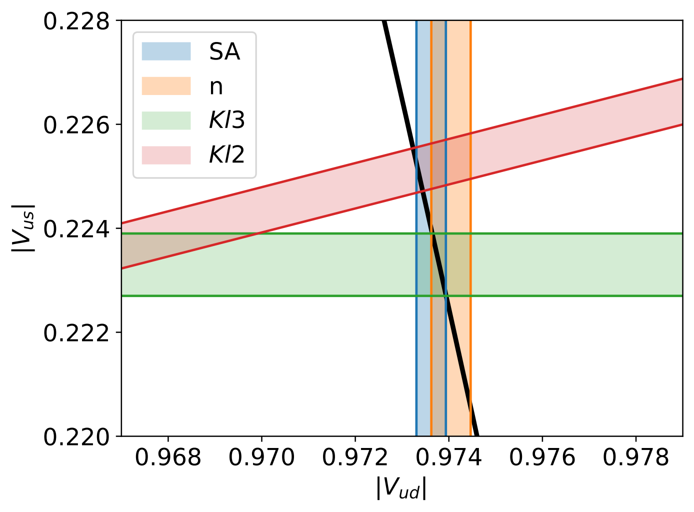
Using most precise τ_n [(877.75(36))] and λ [$-1.27641(56)$]



Uncertainty within 30% of SA, with other equal precision measurement of λ same as SA. Consistent with unitarity

The neutron status

With most precise neutron data $|V_{ud}| = 0.97409(42)$

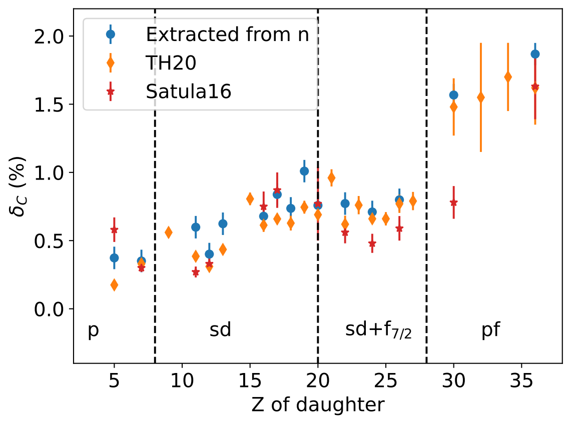


Consistent with unitarity & $Kl2$

The neutron and δ_C

Use neutron ($\delta_C = \delta_{NS} = 0$) to see what δ_C *should be*

$$\delta_C = 1 - \frac{\mathcal{F}t_n}{ft(1+\delta_R')} + \delta_{NS}$$



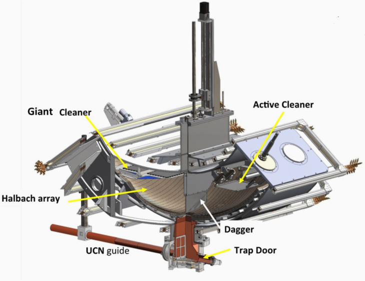
Average shift due to agreement with unitarity, case-by-case due to δ_C or δ_{NS}

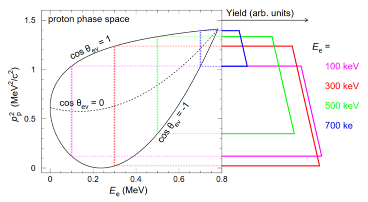
The neutron: Ongoing experiments

Neutrons are unique system, **trappable** when ultracold!

Cherry-picking experiments (See Chen-Yu Liu)

UCN$\tau+$, LANL (bottle τ_n) & Nab, ORNL (g_A from $a_{\beta\nu}$)





UCNτ has current most precise determination of τ_n (0.04%)

Nab is commissioning @ ORNL, aims $\mathcal{O}(0.1\%)$

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Nucleus: $T = 1/2$ Mirror decays

Nuclei with same 'core', initial and final state differ only in valence particle (e.g. ^{3}H & ^{3}He, ^{15}O & ^{15}N)

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$M_F = 1$, but mixed Fermi-Gamow-Teller decay

$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS})\left[1+\frac{f_A}{f_V}\rho^2\right] = \frac{K}{G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

ρ must be determined independently from β correlation, $f_A/f_V \sim 1$ from theory

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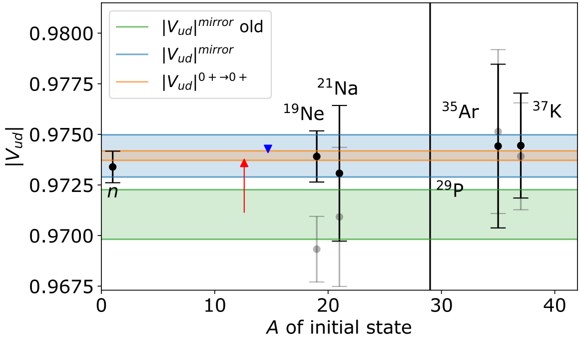
ρ must be determined independently from β correlation, $f_A/f_V \sim 1$ from theory

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto 1 + a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b_F\frac{m_e}{E_e} + A\frac{\vec{p_e}}{E_e}\langle\vec{I}\rangle + \ldots$$

Nucleus: $T = 1/2$ Mirror decays

Resolved double-counting in mirror *RC* significantly increases precision & agreement

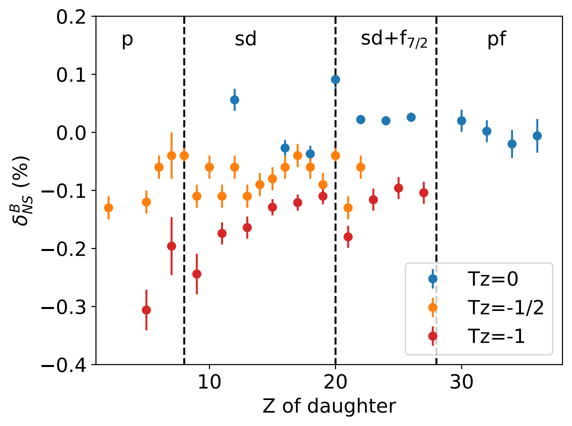


LH, PRD 103 (2021) 113001

$$|V_{ud}|^{\mathrm{mirror}} = 0.9710(12) \longrightarrow |V_{ud}|^{\mathrm{mirror}} = 0.9739(10)$$ 2.5 σ shift

Mirror nuclei and δ_C

Adds substantial amount of new cases for δ_C and δ_{NS}

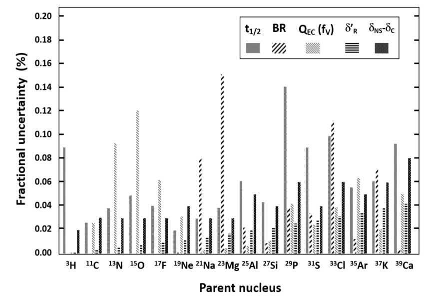


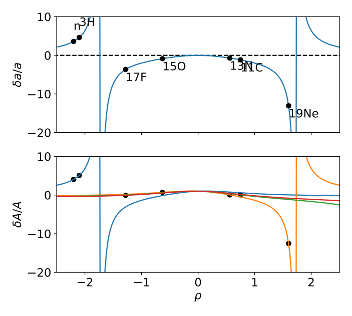
Clear isospin substructures, higher multiplets could be interesting

(N. Severijns, LH, et al., 2109.08895)

Bonus: V_{ud} from $T = 1/2$ mirror decays

Mirror $T = 1/2$ decays are also great V_{ud} tool





Cancellation in correlations gives rise to **great sensitivity**!

LH & Young, 2009.11364; Severijns, LH, et al., 2109.08895; Vanlangendonck et al., PRC 106 015506

Mirror experimental status

Community is investi(gati)ng in different ideas (not exhaustive)

^{6}He-CRES

SALER

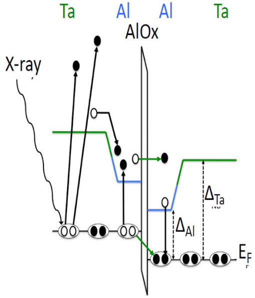
with new spectroscopy techniques & traps.

Additionally, A_β of ^{19}Ne is always good idea due to $\times 13$ enhancement (When working with Albert it's inevitable)

Meet superconducting tunnel junctions

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, making it among the fastest high-resolution quantum sensors available
  → "High" Rate (10^4 s^{-1} per pixel)

↖ *Ideal for RIB experiments at ISAC*



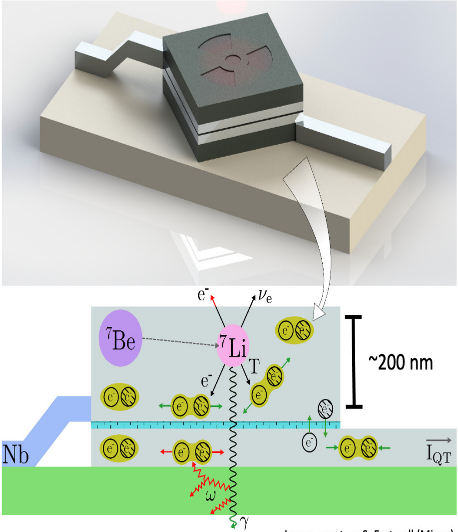
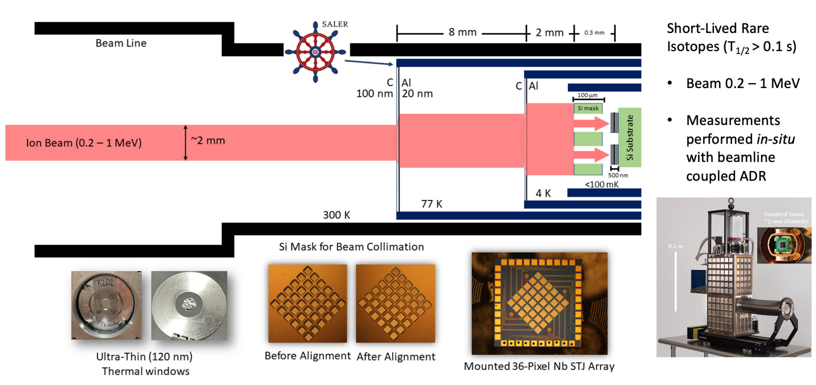


Image courtesy S. Fretwell (Mines)

Superconducting tunnel junctions

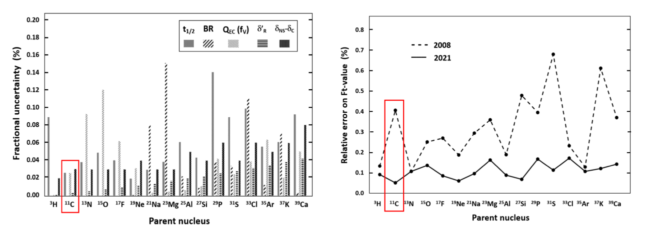
Measure recoiling nucleus instead, and at RIB



Portability allows easy installation (ISAC, SPIRAL2, FRIB, ISOLDE, . . .)

SALER plans

^{11}C first physics target (long $t_{1/2}$, unreachable with traps!)



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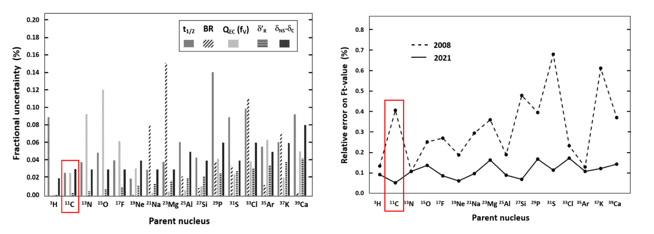
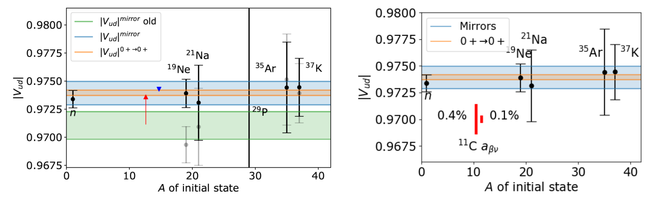


Excellent V_{ud} sensitivity



Successful DOE funding, TRIUMF LOI highly endorsed

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Summary & Outlook

Superallowed $|V_{ud}|$ extraction gained a lot of attention, first time uncertainty *increased*

Several sources of common shifts in δ_{NS}, effects largely cancel but increase uncertainty. Polarization in γW is current bottleneck

δ_C and δ_{NS}^B need theory attention, particularly ^{10}C.

Individual neutron measurements almost as precise as SA, consistent with unitarity, but needs experimental coherence. Useful δ_C tool

Mirrors stay interesting due to enhancement for $|V_{ud}|$, theory cross check for δ_C

Thank you!

U.S. DEPARTMENT OF ENERGY | Office of Science

β recoil spectroscopy

Spectroscopy experiments currently focused on β (e^-/e^+), but extremely demanding

- Detector linearity, energy losses, pile-up,...
- Theory spectrum calculation

Naviliat-Cuncic, Gonzalez-Alonso PRC 94, 035503; LH *et al.*, RMP 90 015008

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Naviliat-Cuncic, Gonzalez-Alonso PRC 94, 035503; LH *et al.*, RMP 90 015008

Instead, recoil spectroscopy has interesting features

- Compressed energy range ($<$keV instead of $\sim$ MeV)
- Electron capture gives single recoil peak
- Sensitive to β-ν correlation for $\beta^{\pm}$ decay

Meet superconducting tunnel junctions

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
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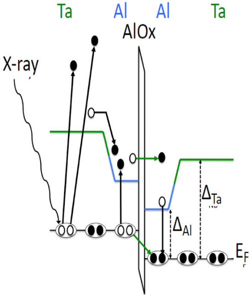
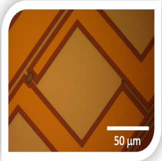




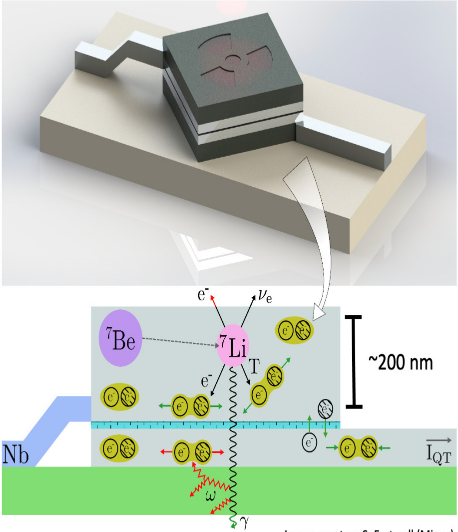


Image courtesy S. Fretwell (Mines)

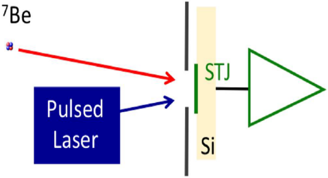
The BeEST experiment (Slide by Kyle Leach)

TRIUMF

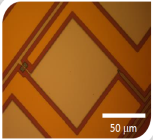
Rare-isotope implantation at TRIUMF-ISAC

THE BeEST

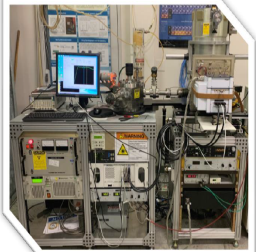
A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.*, J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al.*, J. Low Temp. Phys. **200**, 200 (2020)



Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS



Lawrence Livermore National Laboratory

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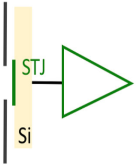
EMPIR EURAMET

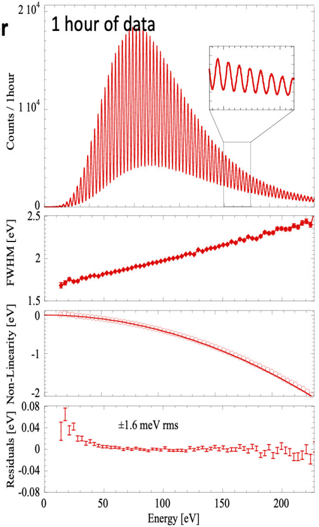
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Superconducting tunnel junctions (Slide by Kyle Leach)



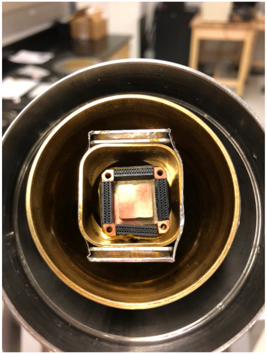
- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage
- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity (10^{-4} per eV)

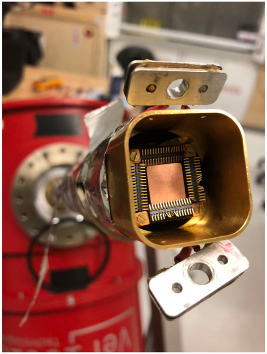
Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK

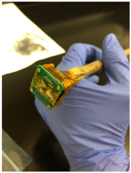


S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

Superconducting tunnel junctions







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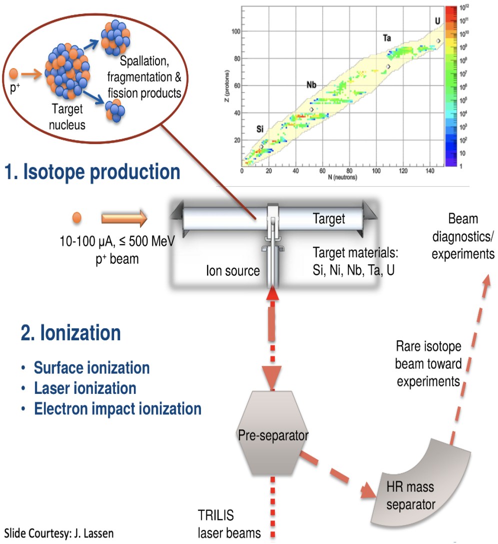
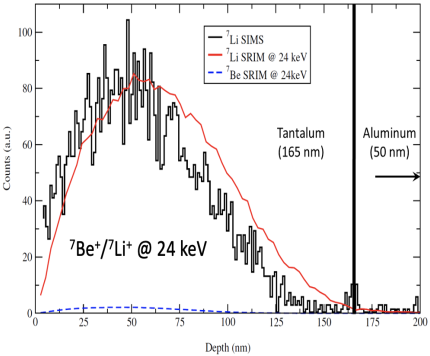


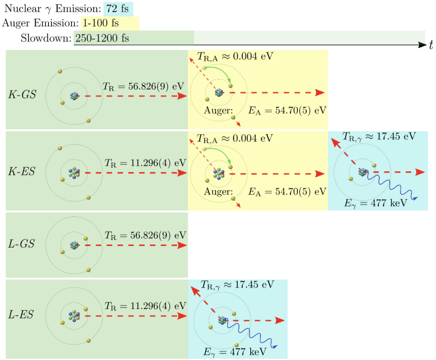


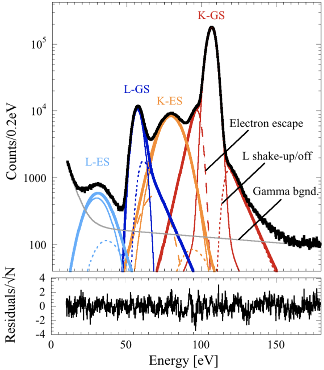
Our current method with ^{7}Be for the BeEST:

- Done at the ISAC Implantation Station
- Inactive (room temperature) sensor array
- Clear and ship sensor to lab (LLNL)
- Receive, handle, and cool to < 100 mK

Superconducting tunnel junctions (Slide by Kyle Leach)

Most precise ^{7}Be L/K capture measurement (PRL 125 (2020) 032701)

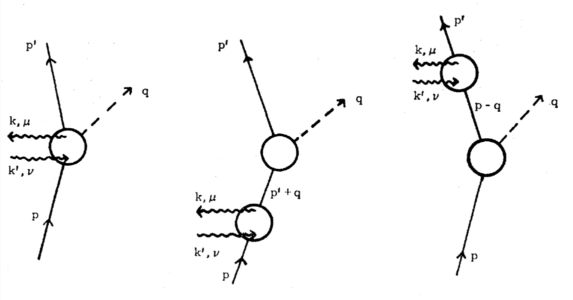




S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

Constraints on MeV-scale sterile neutrino's (PRL 126 (2021) 021803)

Vertex corrections



Use on mass-shell renormalization

$$T_a^{\mu\lambda}{}_\lambda = \frac{C_a}{2(2\pi)^4}\int \frac{d^4k}{k^2 - M_a^2}\int d^4x \int d^4y e^{i\bar{q}\cdot y} e^{ik\cdot x}$$
$$\times \langle p_f | T\{J_W^\mu(y) J_a^\lambda(x) J_\lambda^a(0)\} | p_i\rangle - B_a^\mu$$

where $a \in [\gamma, Z, W]$, subtracts mass poles with B

Vertex corrections

Use Ward-Takahashi identities ($\sim k_\mu \mathcal{M}^\mu = 0$ transverse photons in QED) & algebra to write matrix element

$$\mathcal{M}_v^a = \frac{g^2 C_a}{4(2\pi)^4} V_{ud} \frac{L^\mu}{q^2 - M_W^2} \lim_{\bar{q}\to q} \left[-\bar{q}_\nu \frac{\partial}{\partial \bar{q}^\mu} T_a^\nu + \frac{\partial}{\partial \bar{q}^\mu} \left\{ \mathcal{D}_a + \mathcal{Z}_a{}^\lambda{}_\lambda - \bar{q}_\nu B_a^\nu \right\} \right]$$

with separate 2-point and 3-point contributions

Vertex correction: 3p

3-point correlation function

$$\mathcal{D}_a = \int \frac{d^4k}{k^2 - M_a^2} \int d^4y e^{i\bar{q}y} \int d^4x e^{ikx}$$
$$\times \langle p_f | T \left\{ \partial_\mu J_W^\mu(y) J_a^\lambda(x) J_\lambda^a(0) \right\} |p_i\rangle$$

For vector transitions $\partial_\mu J_W^\mu \approx 0$, found our **first difference**

Vertex correction: 3p

3-point correlation function

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For vector transitions $\partial_\mu J_W^\mu \approx 0$, found our **first difference**

Heavy EW bosons only give negligible $\mathcal{O}(G_F^2)$ contributions since integral is IR convergent, only care about γ

Vertex correction: 3p

Strategy: look at IR and UV limits separately

Vertex correction: 3p

Strategy: look at IR and UV limits separately

UV is straightforward (OPE/BJL limit) and vanishes

Can be understood as 'soft breaking' of axial current ($m_\pi \to 0$)

$$\mathcal{D}_\gamma \approx \mathcal{D}_\gamma^{\text{elastic}}$$

Vertex correction: 3p

Elastic response contains cancellation between isoscalar & isovector photon charges

$$D_\gamma^{\text{elastic}} = \left[(Q^S)^2 - (Q^V)^2\right] 2g_A M \left(1 + \frac{q^2}{m_\pi^2}\right) [\bar{N}'\gamma^5 T^\pm N] \times \int \frac{d^4k}{k^2} \frac{M^2}{M^2 - k^2} \frac{1}{k_0^2 + i\epsilon}$$

In isospin limit $Q^S = Q^V \to \mathcal{D}_\gamma = 0$, coincidential disappearance?

Box diagram: D

Depends on derivative

$$\mathcal{D}_\mu^\gamma = i \int d^4x e^{i(k-q)\cdot x} \langle p_f | T\{\partial^\nu J_\nu^W(x) J_\mu^\gamma(0)\}|p_i\rangle,$$

Like above, we have found **another difference**

Box diagram: D

Depends on derivative

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Like above, we have found **another difference**

Once again, UV disappears (PCAC) and so does elastic

$$\mathcal{D}_\mu^{\mathrm{elastic}} \propto Q^V \bar{N} \left[\tau^z \partial_\nu J_W^\nu + \partial_\nu J_W^\nu \tau^z\right] N,$$

now due to crossing symmetry ($\{\tau^z, \tau^\pm\} = 0$)

Recent changes: *RC*

Change in Δ_R^V corresponds to change in $|V_{ud}|$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(5) \to 0.9984(4)$$

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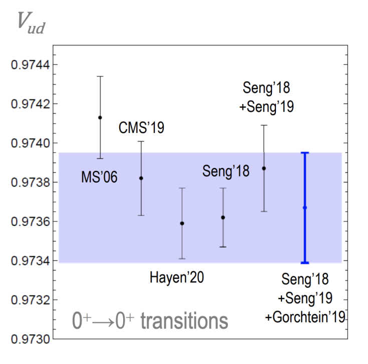
Additional quasi/inelastic nuclear structure should be included

$0.9984(4) \to 0.9989(5) \to 0.9984(6)$



AF, MG-A, ON-C, 2010.13797

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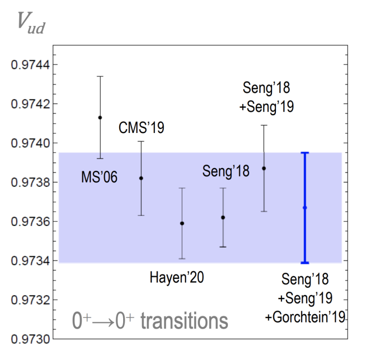
You win some, . . .

Gorchtein, PRL 123 (2019) 042503



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Tools

Can leverage current algebra, predating SM (60's)

Assume electroweak currents form $SU(3)$ octet, postulate equal-time commutation relations

$$\begin{aligned}
\left[J^0_\gamma(\boldsymbol{x}), J^\mu_W(0)\right] &= J^\mu_W(\boldsymbol{x})\delta^{(3)}(\boldsymbol{x}) \\
\left[J^0_W(\boldsymbol{x}), J^\mu_Z(0)\right] &= \cos^2\theta_W J^\mu_W(\boldsymbol{x})\delta^{(3)}(\boldsymbol{x}) \\
\left[J^0_W(\boldsymbol{x}), J^\mu_W(0)\right] &= -2\left[\sin^2\theta_W J^\mu_\gamma(\boldsymbol{x}) + J^\mu_Z(\boldsymbol{x})\right]\delta^{(3)}(\boldsymbol{x})
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Commutation relations turn out to be conserved even in presence of QCD