Recent advances in β decay and possible future avenues

Leendert Hayen

DND Meeting, Nov 5th 2020

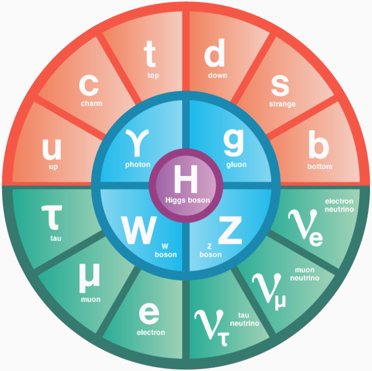
NC State & TUNL, USA

Contents

Table of Contents

Introduction: Standard Model

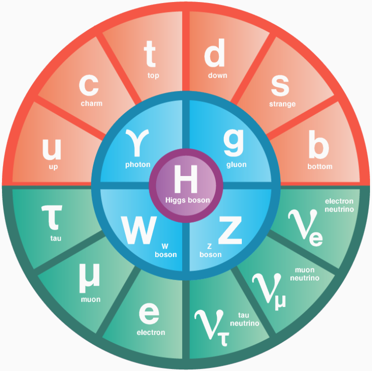
'Simple' gauge groups:
$SU(3)_c \times SU(2)_L \times U(1)_Y$



Introduction: Standard Model

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

18-26 free parameters

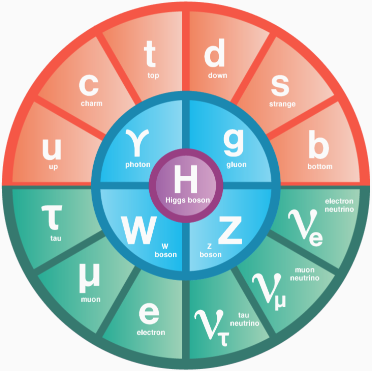


Introduction: Standard Model

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

18-26 free parameters

Great (annoyingly so), consistent with constraints at $\sim 10^{0-2}$ TeV



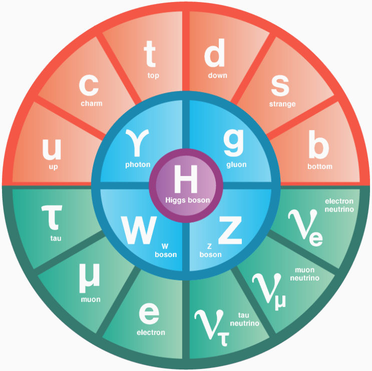
Introduction: Standard Model

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

18-26 free parameters

Great (annoyingly so), consistent with constraints at $\sim 10^{0-2}$ TeV

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



Introduction: Standard Model

SM tests @ low energy: non-perturbative QCD very difficult $\rightarrow$ predominantly electroweak

Introduction: Standard Model

SM tests @ low energy: non-perturbative QCD very difficult $\rightarrow$ predominantly electroweak

Besides precision QED ($a_{e,\mu}, r_p, \ldots$), weak interactions probe

- (C)P violation
- Lorentz structure
- CKM unitarity

Introduction: Standard Model

SM tests @ low energy: non-perturbative QCD very difficult $\rightarrow$ predominantly electroweak

Besides precision QED ($a_{e,\mu}$, r_p, ...), weak interactions probe

- (C)P violation
- Lorentz structure
- CKM unitarity

All of these can be probed using **(nuclear)** β **decay**

Introduction: Standard Model

SM tests @ low energy: non-perturbative QCD very difficult $\rightarrow$ predominantly electroweak

Besides precision QED ($a_{e,\mu}$, r_p, ...), weak interactions probe

- (C)P violation
- Lorentz structure Today
- CKM unitarity Today

All of these can be probed using **(nuclear)** β **decay**

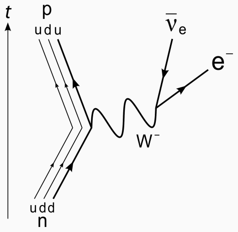
Introduction: β decay

Advantages

Typical β decay scale $\ll M_W$

$\rightarrow$ V-A 4-point tree level + QCD + QED

$\rightarrow$ Constant renormalization of coupling constants



Nuclear chart sandbox

Introduction: β decay

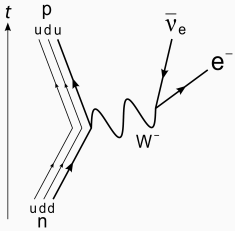
Advantages

Typical β decay scale $\ll M_W$

$\rightarrow$ V-A 4-point tree level + QCD + QED

$\rightarrow$ Constant renormalization of coupling constants

Nuclear chart sandbox



Challenges

Strong many-body physics

High precision requires quark $\rightarrow$ nucleus $\rightarrow$ atom corrections

Workshops

Lots of activity following 3 timely workshops

- Nov 2018: ACFI UMass
- April 2019: ECT* Trento
- Nov 2019: INT @ UW

Table of Contents

CKM unitarity

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

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

CKM unitarity

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

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

Unitarity requires

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

CKM unitarity

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

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

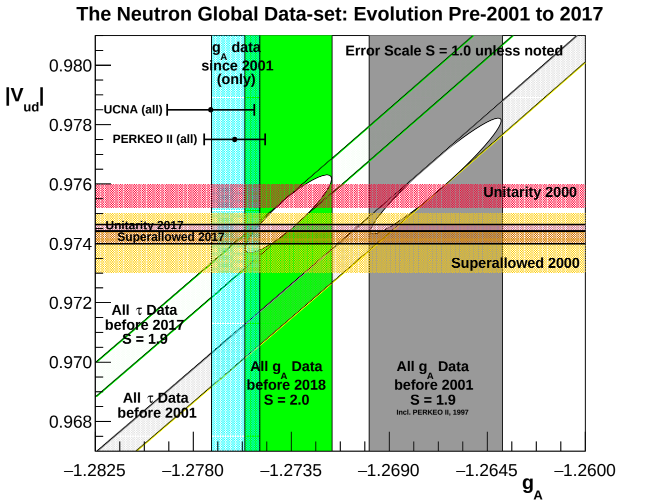
Unitarity requires

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

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

CKM unitarity: 2001-2017

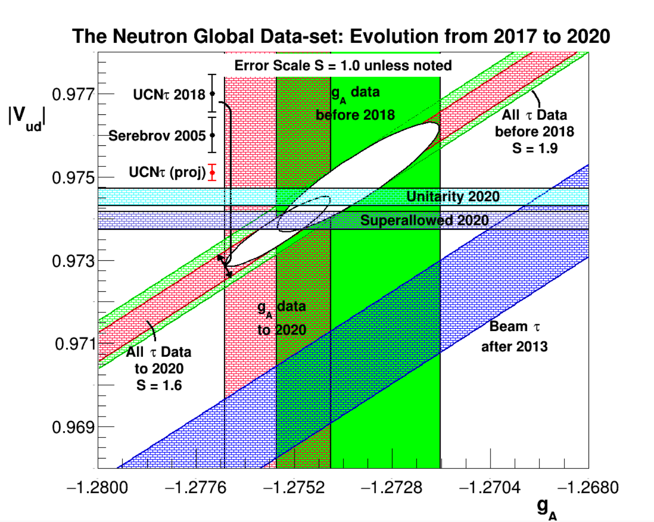
Quite some movement over the years...



Thanks to Albert Young

CKM unitarity: 2018-2020

Quite some movement over the years...



Thanks to Albert Young

CKM unitarity: V_{us}

The plot thickens: disagreement between $Kl2$ and $Kl3$ $|V_{us}|$
'Cabibbo angle anomaly'

- $|V_{us}| = 0.2234(8)$ $(K \to \pi l \nu)$
- $|V_{us}| = 0.2253(4)$ $(K^{\pm} \to l^{\pm} \nu)$

Early signs of new physics? Lattice QCD artifacts? Time will tell

Czarnecki, Marciano, Sirlin PRD 101 (2020) 019301

Table of Contents

Recent changes: *RC*

Radiative corrections can ($\sim$) be separated into

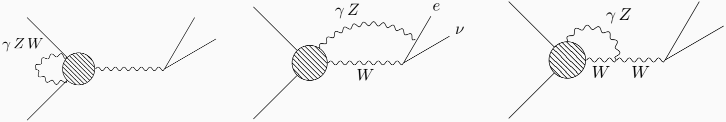
1. Energy-dependent, QCD-*in*dependent part: δ_R
2. Energy-*in*dependent, QCD-dependent part: Δ_R

Recent changes: *RC*

Radiative corrections can ($\sim$) be separated into

1. Energy-dependent, QCD-*in*dependent part: δ_R
2. Energy-*in*dependent, QCD-dependent part: Δ_R

δ_R sufficiently known. Δ_R depends on



vertex correction, box diagrams, $\sim$ penguin

$+$ others. Generally well-understood from current algebra & pQCD

Recent changes: *RC*

Everything OK except (in)famous axial contribution in γW box

$$\Box_{\gamma W}^{VA} = \frac{\alpha}{8\pi} \int_0^\infty dQ^2 \frac{M_W^2}{Q^2 + M_W^2} F(Q^2)$$

sensitive everywhere $Q^2 \to 0$ (IR), $Q^2 \sim M_n^2$ (Nuclear + inelastic), $Q^2 \gtrsim M_W^2$ (UV + pQCD)

Recent changes: *RC*

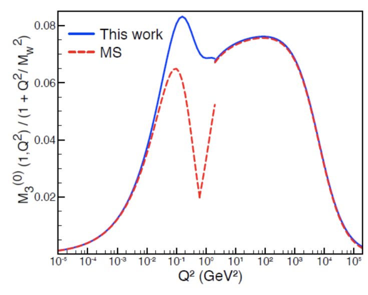
Everything OK except (in)famous axial contribution in γW box

$$\Box^{VA}_{\gamma W} = \frac{\alpha}{8\pi}\int_0^\infty dQ^2 \frac{M_W^2}{Q^2+M_W^2} F(Q^2)$$

sensitive everywhere $Q^2 \to 0$ (IR), $Q^2 \sim M_n^2$ (Nuclear + inelastic), $Q^2 \gtrsim M_W^2$ (UV + pQCD)

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



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

Recent changes: *RC*

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

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

Recent changes: *RC*

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

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

4 σ unitarity violation? Nuclear theory error? V_{us}?

Recent changes: *RC*

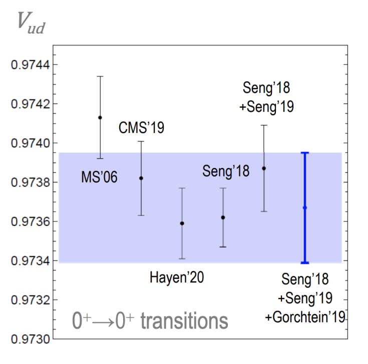
Change in Δ_R^V corresponds to change in $|V_{ud}|$

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

4 σ unitarity violation? Nuclear theory error? V_{us}?

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

Recent changes: *RC*

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

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

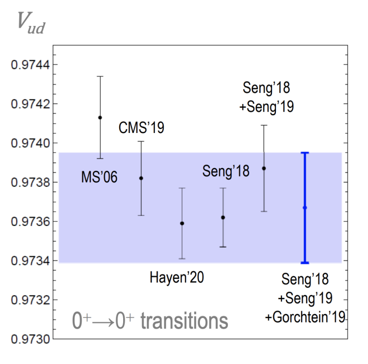
4 σ unitarity violation? Nuclear theory error? V_{us}?

Additional quasi/inelastic nuclear structure should be included

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

You win some, ...

Gorchtein, PRL 123 (2019) 042503



AF, MG-A, ON-C, 2010.13797

Recent changes: *RC*

So far only Δ_R^V was calculated, what about Δ_R^A

$$g_A^{\text{exp}} = g_A \left[1 + \frac{1}{2}(\Delta_R^A - \Delta_R^V) + \delta_{BSM} \right]$$

NC↔CC and comparison to lattice QCD for right-handed currents

Recent changes: *RC*

So far only Δ_R^V was calculated, what about Δ_R^A

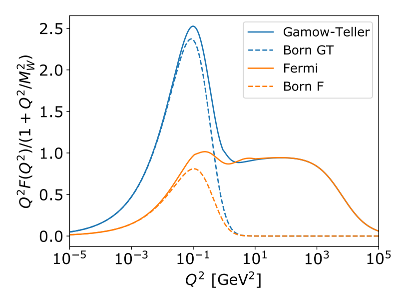
$$g_A^{\mathrm{exp}} = g_A \left[1 + \frac{1}{2}(\Delta_R^A - \Delta_R^V) + \delta_{BSM}\right]$$

NC↔CC and comparison to lattice QCD for right-handed currents

New calculation

- $\Delta_R^A = 0.02881(30)$
- $\Delta_R^V = 0.02474(31)$

$\Delta_R^A - \Delta_R^V = 4.07(8) \times 10^{-3}$



LH, 2010.07262

Recent changes: *RC*

So far only Δ_R^V was calculated, what about Δ_R^A

$$g_A^{\exp} = g_A \left[1 + \frac{1}{2}(\Delta_R^A - \Delta_R^V) + \delta_{BSM}\right]$$

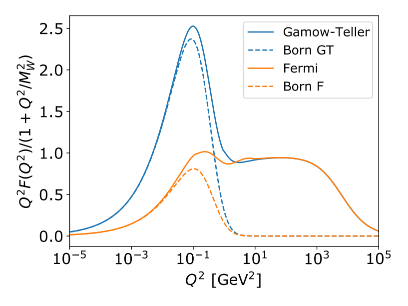
NC↔CC and comparison to lattice QCD for right-handed currents

New calculation

- $\Delta_R^A = 0.02881(30)$
- $\Delta_R^V = 0.02474(31)$

$\Delta_R^A - \Delta_R^V = 4.07(8) \times 10^{-3}$

Much larger than
usually assumed ($\lesssim 0.1\%$)!



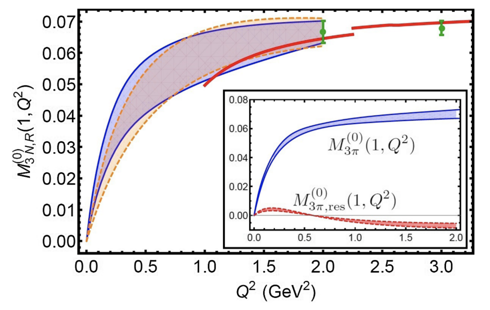
LH, 2010.07262

Role of LQCD

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

Role of LQCD

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

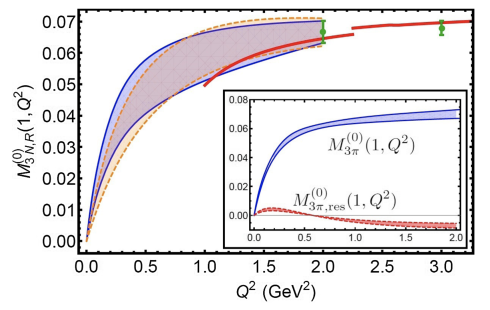


Seng *et al.*, PRD 101 111301

Use pions & relate to nucleon

Role of LQCD

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



Seng *et al.*, PRD 101 111301

Use pions & relate to nucleon

Efforts underway for $\Delta_R^A + \Delta_R^V$ from χPT & LQCD

Table of Contents

CKM unitarity: V_{ud}

Get $|V_{ud}|$ from 'corrected' ft value

$$\mathcal{F}t \equiv f_V t_{1/2} M_F^2 (1+\delta_R)(1+\text{stuff}) = \frac{K}{G_F^2 |V_{ud}|^2 (1+\Delta_R^V)}$$

All relevant β transitions have same RHS

CKM unitarity: V_{ud}

Get $|V_{ud}|$ from 'corrected' ft value

$$\mathcal{F}t \equiv f_V t_{1/2} M_F^2 (1+\delta_R)(1+\text{stuff}) = \frac{K}{G_F^2 |V_{ud}|^2 (1+\Delta_R^V)}$$

All relevant β transitions have same RHS

Nuclear sandbox $\rightarrow$ make $M_F^2(1+\text{stuff})$ easy

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

CKM unitarity: V_{ud}

Get $|V_{ud}|$ from 'corrected' ft value

$$\mathcal{F}t \equiv f_V t_{1/2} M_F^2 (1+\delta_R)(1+\text{stuff}) = \frac{K}{G_F^2 |V_{ud}|^2 (1+\Delta_R^V)}$$

All relevant β transitions have same RHS

Nuclear sandbox → make $M_F^2(1+\text{stuff})$ easy

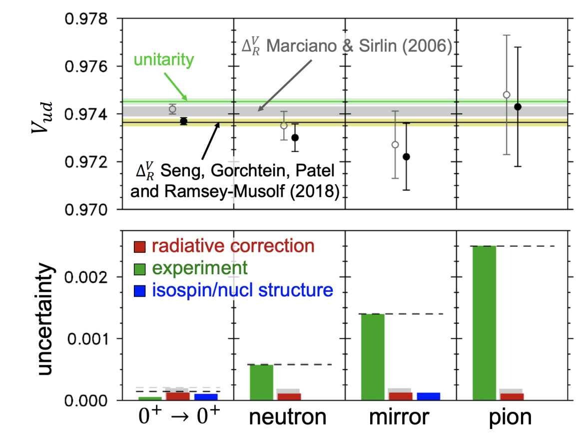
- Neutron
- Superallowed $0^+ \to 0^+$
- $T = 1/2$ mirrors

Fermi matrix element known from isospin symmetry

→ small corrections (+ GT/F from correlation measurement)

CKM unitarity: V_{ud} precision

Status early 2019



- $0^+ \to 0^+$:
  $V_{ud} = 0.9742(2)$
  $\to \; 0.9737(1)$
- The neutron
  $V_{ud} = 0.9735(6)$
  $\to \; 0.9730(6)$
- Mirror transitions
  $V_{ud} = 0.9727(14)$
  $\to \; 0.9722(14)$
- The pion
  $V_{ud} = 0.9748(25)$
  $\to \; 0.9743(25)$

Modified from D. Malconian, ECT* 2019

The neutron

Neutron is *theoretically* cleanest system

The neutron

Neutron is *theoretically* cleanest system

Experimentally, need to know

- Q_β ✓
- Branching ratio ✓
- $\lambda = g_A/g_V$
- $t_{1/2}$

The neutron

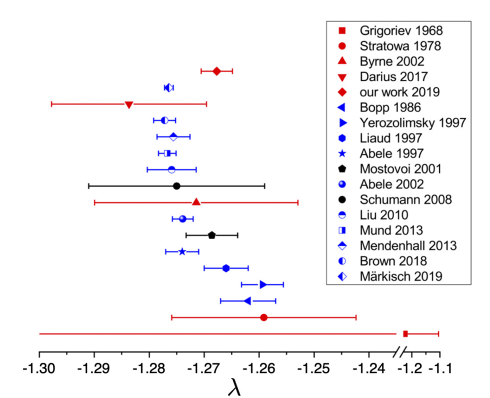
Neutron is *theoretically* cleanest system

Experimentally, need to know

- Q_β ✓
- Branching ratio ✓
- $\lambda = g_A/g_V$
- $t_{1/2}$

The neutron: λ

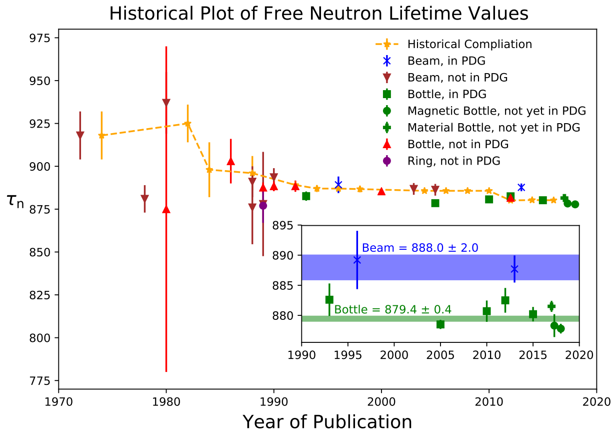
Evolution of $\lambda = g_A/g_V$



Tension between PERKEO3 and aSPECT, both 2019

The neutron: τ_n

Evolution of τ_n



Bottle: Count survivors; Beam: Count decay products

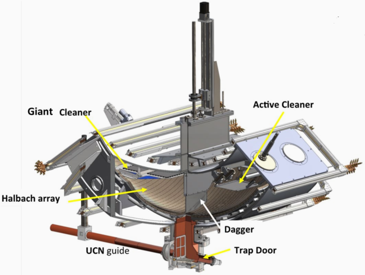
The neutron: τ_n

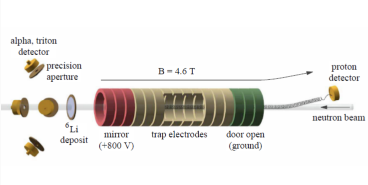
Essential physics ingredient: Big Bang Nucleosynthesis, solar physics, reactor anomaly, ...

The neutron: τ_n

Essential physics ingredient: Big Bang Nucleosynthesis, solar physics, reactor anomaly, ...

Current US based efforts mainly UCNτ @ LANSCE (bottle) & BL2/3 @ NIST (beam)





Several R&D efforts to combine (UCNProbe, HOPE, ...)

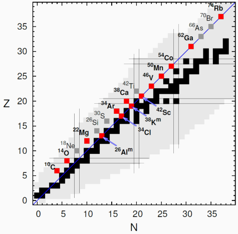
Nucleus: Superallowed $0^+ \to 0^+$

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

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

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

$\delta V_{ud}/V_{ud} \approx 0.04\%$

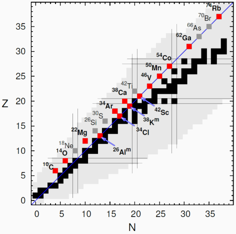


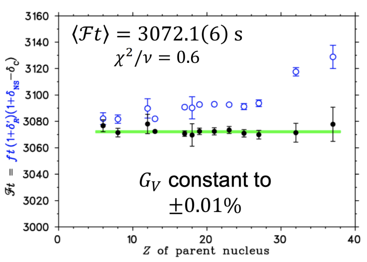
Pure Fermi transitions, $M_F = \sqrt{2}$

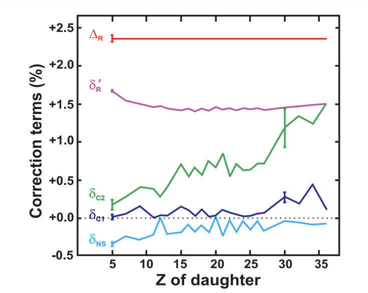
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

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

$\delta V_{ud}/V_{ud} \approx 0.04\%$







Towner & Hardy analysis; Plots by J. Hardy & D. Malconian

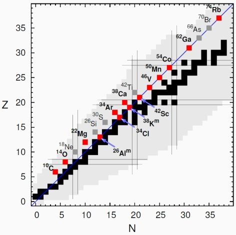
Nucleus: Superallowed $0^+ \to 0^+$

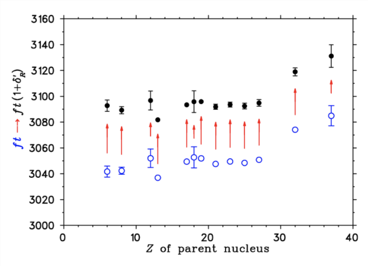
Pure Fermi transitions, $M_F = \sqrt{2}$

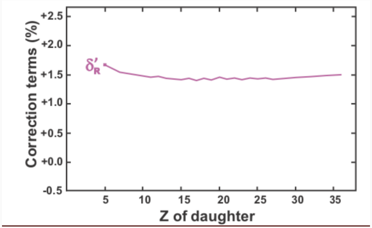
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

Few small $\mathcal{O}(0.1\% - 2\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.04\%$







Additional photonic corrections

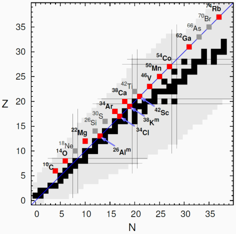
Nucleus: Superallowed $0^+ \to 0^+$

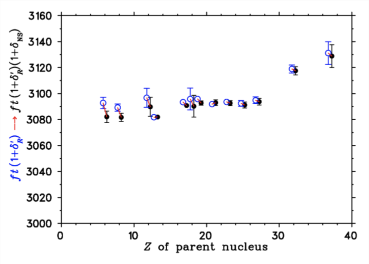
Pure Fermi transitions, $M_F = \sqrt{2}$

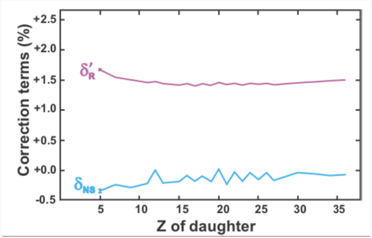
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

Few small $\mathcal{O}(0.1\% - 2\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.04\%$







Nuclear effects in RC (2BC)

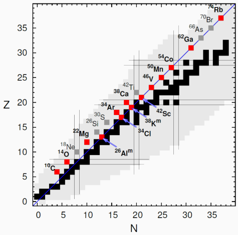
Nucleus: Superallowed $0^+ \to 0^+$

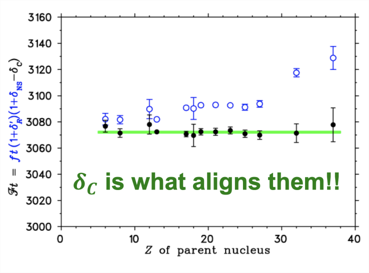
Pure Fermi transitions, $M_F = \sqrt{2}$

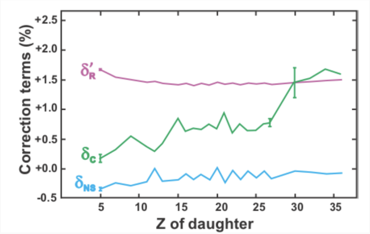
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

Few small $\mathcal{O}(0.1\% - 2\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.04\%$







Isospin breaking. How sure are we of δ_C?

Nucleus: Isospin breaking corrections

In this context: proton $\neq$ neutron inside nucleus
$\rightarrow M_F^2 = 2(1 - \delta_C)$

- Different radial wave function (Coulomb)
- Configuration interaction difference initial $\leftrightarrow$ final

Nucleus: Isospin breaking corrections

In this context: proton $\neq$ neutron inside nucleus
$\rightarrow M_F^2 = 2(1 - \delta_C)$

- Different radial wave function (Coulomb)
- Configuration interaction difference initial $\leftrightarrow$ final

Compilations used Woods-Saxon potentials in shell model, but ab initio is maturing

$\rightarrow$ well-defined uncertainties & minimal data fitting

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)

Nucleus: $T = 1/2$ Mirror decays

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

$M_F = 1$, 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

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)

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

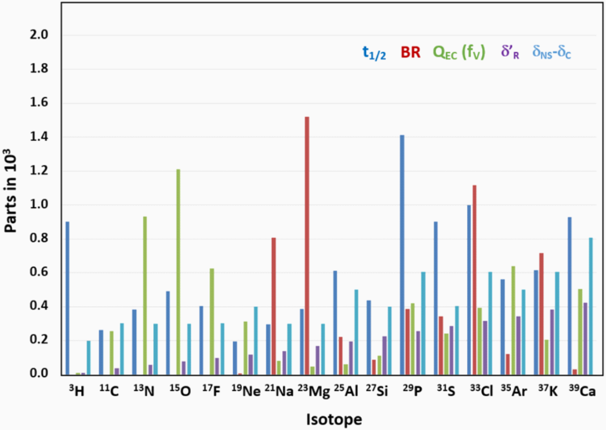
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS})\left[1+\frac{f_A}{f_V}\rho^2\right] = \frac{K}{G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

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

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

Nucleus: $T = 1/2$ Mirror decays

Current precision status for $f_V t(1+\delta_R)(1+\delta_{NS}-\delta_C)$



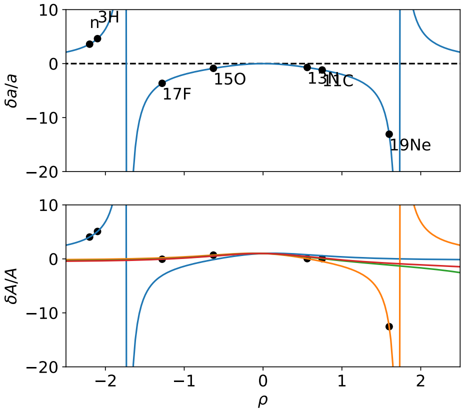
N. Severijns, LH *et al.*, In preparation

Nucleus: $T = 1/2$ Mirror decays

For V_{ud} extraction ρ is typically bottleneck

Mixed transition causes cancellation $\rightarrow$ enhanced sensitivity

Neutron and ^{19}Ne have factor 5-13 enhancement for ρ!



LH, A. Young, 2009.11364

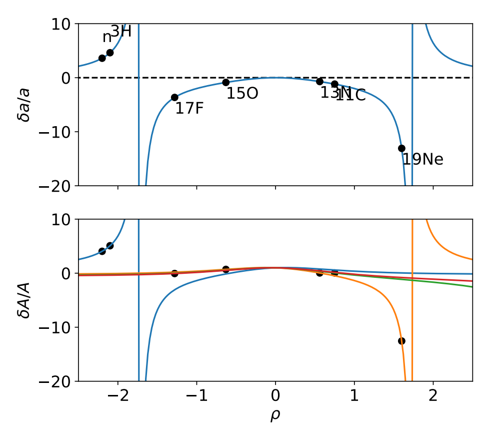
Nucleus: $T = 1/2$ Mirror decays

For V_{ud} extraction ρ is typically bottleneck

Mixed transition causes cancellation $\rightarrow$ enhanced sensitivity

Neutron and ^{19}Ne have factor 5-13 enhancement for ρ!

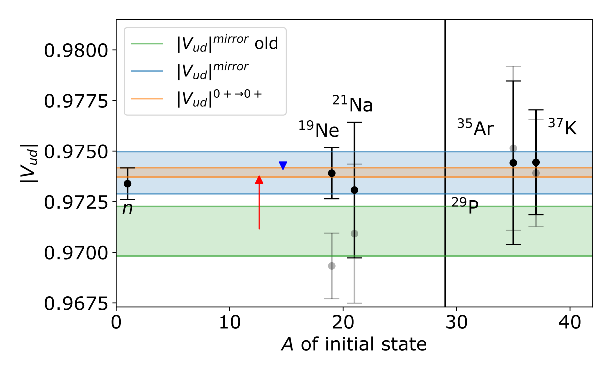
Consistent formalism released (RC, nuclear, geometry), event generator (CRADLE++) in development



LH, A. Young, 2009.11364

Nucleus: $T = 1/2$ Mirror decays

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

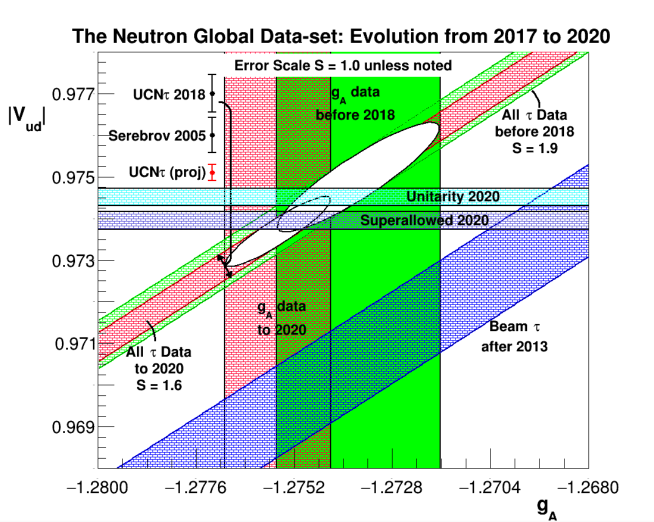


LH, 2010.07262

$$|V_{ud}|^{\text{mirror}} = 0.9710(12) \longrightarrow |V_{ud}|^{\text{mirror}} = 0.9739(10)$$

CKM unitarity: 2018-2020

To summarize



Thanks to Albert Young

Table of Contents

Weak Lorentz structure

Standard Model has V-A structure, but more generally

$$\mathcal{L}_{\text{eff}} = -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu [1 - (1 - 2\epsilon_R)\gamma^5] d + \epsilon_S\, \bar{e}\nu_L \cdot \bar{u}d$$

$$- \epsilon_P\, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T\, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1 - \gamma^5) d \Big\} + \text{h.c.},$$

with

$$\tilde{V}_{ud} = V_{ud}(1 + \epsilon_L + \epsilon_R - \delta G_F / G_F)$$

Weak Lorentz structure

Standard Model has V-A structure, but more generally

$$\mathcal{L}_{\text{eff}} = -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu [1 - (1 - 2\epsilon_R)\gamma^5] d + \epsilon_S \, \bar{e}\nu_L \cdot \bar{u}d - \epsilon_P \, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T \, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1 - \gamma^5) d \Big\} + \text{h.c.},$$

with

$$\tilde{V}_{ud} = V_{ud}(1 + \epsilon_L + \epsilon_R - \delta G_F / G_F)$$

All ϵ_i are proportional to $(M_W/\Lambda_{BSM})^2$, change kinematics

$\epsilon_i \lesssim 10^{-4} \rightarrow \Lambda_{BSM} \gtrsim 15$ TeV assuming natural couplings

Lattice QCD comparison

Comparison with LQCD is clean test for ϵ_R

$$g_A^{\text{exp}} = g_A^{LQCD}\left[1 + \frac{1}{2}(\Delta_R^A - \Delta_R^V)\right](1 - 2\text{Re}\,\epsilon_R)$$

Lattice QCD comparison

Comparison with LQCD is clean test for ϵ_R

$$g_A^{\text{exp}} = g_A^{LQCD}\left[1 + \frac{1}{2}(\Delta_R^A - \Delta_R^V)\right](1 - 2\text{Re}\,\epsilon_R)$$

FLAG19:

$g_A = 1.251(33)$;

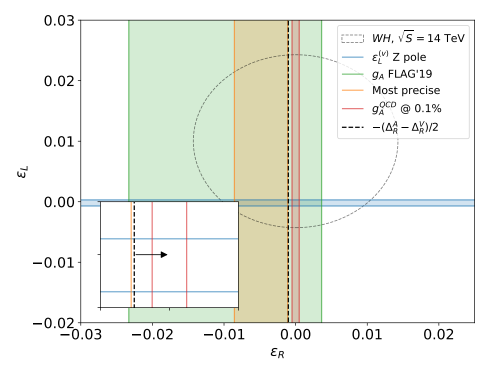
Highest precision:

$g_A = 1.2642(93)$

$\Delta_R^A - \Delta_R^V$

is 2σ effect when

g_A^{LQCD} reaches 0.1%



LH, 2010.07262

BSM sensitivity

New Lorentz structures change correlations

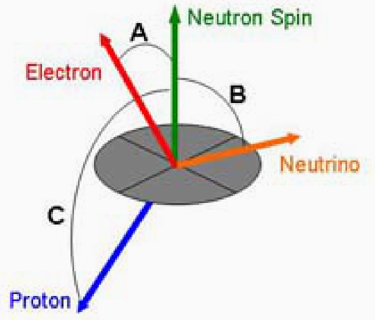
$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto 1 + a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b_F\frac{m_e}{E_e} + A\frac{\vec{p_e}}{E_e}\langle\vec{I}\rangle + \dots$$

In practice,

measure effective correlations

$$\tilde{X} = \frac{X}{1 + b_F\langle\frac{m_e}{E_e}\rangle}$$

BSM sensitivity mainly from b_F



Fierz interference

Interference term $\rightarrow$ linear in exotic couplings

$$b_F = \pm 2\gamma \frac{1}{1+\rho^2} \mathrm{Re}\left\{ \frac{g_S \epsilon_S}{g_V(1+\epsilon_L+\epsilon_R)} + \rho^2 \frac{4 g_T \epsilon_T}{-g_A(1+\epsilon_L-\epsilon_R)} \right\}$$

i.e. 0 in SM

Fierz interference

Interference term → linear in exotic couplings

$$b_F = \pm 2\gamma \frac{1}{1+\rho^2} \mathrm{Re}\left\{ \frac{g_S \epsilon_S}{g_V(1+\epsilon_L+\epsilon_R)} + \rho^2 \frac{4 g_T \epsilon_T}{-g_A(1+\epsilon_L-\epsilon_R)} \right\}$$

i.e. 0 in SM

Get $g_i = \langle p | d O_i \bar{u} | n \rangle \sim 1$ from LQCD

Fierz interference

Interference term → linear in exotic couplings

$$b_F = \pm 2\gamma \frac{1}{1+\rho^2} \mathrm{Re} \left\{ \frac{g_S \epsilon_S}{g_V(1+\epsilon_L+\epsilon_R)} + \rho^2 \frac{4 g_T \epsilon_T}{-g_A(1+\epsilon_L-\epsilon_R)} \right\}$$

i.e. 0 in SM

Get $g_i = \langle p | d O_i \bar{u} | n \rangle \sim 1$ from LQCD

Fermi → scalar, Gamow-Teller → tensor

Fierz interference: Spectrum shape

Measure Fierz directly through the β spectrum shape

$$P(E_e) = \text{Standard Model} \times \left(1 + b_F \frac{m_e}{E_e}\right)$$

Fierz interference: Spectrum shape

Measure Fierz directly through the β spectrum shape

$$P(E_e) = \text{Standard Model} \times \left(1 + b_F \frac{m_e}{E_e}\right)$$

Extremely demanding for

- Detector linearity, energy losses, pile-up,...
- Theory spectrum calculation ($\leftrightarrow$ relative correlation measurements)

Fierz interference: Spectrum shape

Measure Fierz directly through the β spectrum shape

$$P(E_e) = \text{Standard Model} \times \left(1 + b_F \frac{m_e}{E_e}\right)$$

Extremely demanding for

- Detector linearity, energy losses, pile-up,...
- Theory spectrum calculation ($\leftrightarrow$ relative correlation measurements)

Feasible because simulation quality & new techniques like CRES

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

EC/β^+

Ratio measurement has strong benefits

$$\frac{\lambda_{EC}}{\lambda_{\beta^+}} = \sum_{x=K,L,\ldots} \frac{f_x}{f_{\beta^+}} \left[\frac{1+b_F/W_x}{1-b_F/\overline{W}}\right](1 + 0.001 \times \delta_{\text{theory}})$$

Enhanced sensitivity to b_F compared to usual $b_F\langle m_e/E_e\rangle$!

EC/β^+

Ratio measurement has strong benefits

$$\frac{\lambda_{EC}}{\lambda_{\beta^+}} = \sum_{x=K,L,\ldots} \frac{f_x}{f_{\beta^+}} \left[\frac{1+b_F/W_x}{1-b_F/\overline{W}}\right] (1 + 0.001 \times \delta_{\text{theory}})$$

Enhanced sensitivity to b_F compared to usual $b_F \langle m_e/E_e \rangle$!

- At least 3× more sensitive than neutron
- Only sensitive to nuclear structure at $\mathcal{O}(\leq 10^{-3})$
- Radiative corrections $\mathcal{O}(10^{-3})$, semi-known (f_{EC})

EC/β^+

Ratio measurement has strong benefits

$$\frac{\lambda_{EC}}{\lambda_{\beta^+}} = \sum_{x=K,L,\ldots} \frac{f_x}{f_{\beta^+}} \left[\frac{1+b_F/W_x}{1-b_F/\overline{W}}\right] (1 + 0.001 \times \delta_{\text{theory}})$$

Enhanced sensitivity to b_F compared to usual $b_F\langle m_e/E_e\rangle$!

- At least $3\times$ more sensitive than neutron
- Only sensitive to nuclear structure at $\mathcal{O}(\leq 10^{-3})$
- Radiative corrections $\mathcal{O}(10^{-3})$, semi-known (f_{EC})

Experimentally interesting

- 'Simpler' counting experiment, could be done with 1 detector
- Systematics drop out in ratio

EC/β^+

Choose decays to excited nuclear states $\rightarrow \gamma$ coincidence for BG reduction (^{22}Na, ^{43}Sc, ^{58}Co, ...)

EC/β^+

Choose decays to excited nuclear states $\rightarrow \gamma$ coincidence for BG reduction (^{22}Na, ^{43}Sc, ^{58}Co, ...)

Interesting test for atomic physics calculations, great progress with m_ν searches in ^{163}Ho ($+$ use K, L, M capture for consistency)

EC/β^+

Choose decays to excited nuclear states $\rightarrow \gamma$ coincidence for BG reduction (^{22}Na, ^{43}Sc, ^{58}Co, ...)

Interesting test for atomic physics calculations, great progress with m_ν searches in ^{163}Ho (+ use K, L, M capture for consistency)

Counting works, energy dependence is even better $\rightarrow$ distinguish different shell captures & fit b_F/W. Looking into detector technology

Atomic physics with β decay

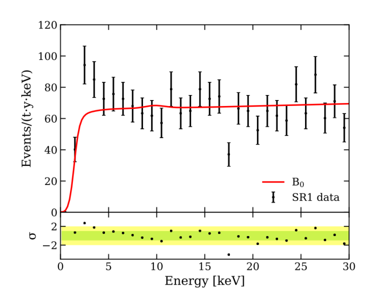
β^- decay has atomic exchange effect: e^- decays into bound state

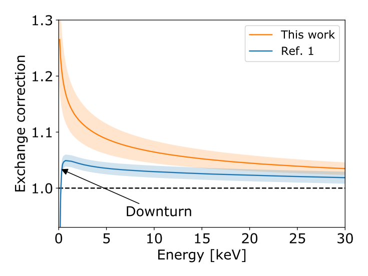
$\rightarrow$ **strong** enhancement near low energy

Atomic physics with β decay

β^- decay has atomic exchange effect: e^- decays into bound state $\rightarrow$ **strong** enhancement near low energy

X1T excess, ^{214}Pb background





Aprile *et al.*, 2006.09721; LH, Simonucci, Taioli, 2009.08303

DM & ALP backgrounds dominated by β decays $\rightarrow$ unexplored atomic effects $\rightarrow$ measure in CRES + atom traps?

Table of Contents

Summary & Outlook

Past year(s) has seen several significant changes

- New RC are changing the game for $|V_{ud}|$
- $Kl2/Kl3$ discrepancy for $|V_{us}|$ opened
- Ab initio entering isospin breaking calculations
- New neutron results confirm (τ_n) and create new (λ) tensions

Summary & Outlook

Past year(s) has seen several significant changes

- New RC are changing the game for $|V_{ud}|$
- $Kl2/Kl3$ discrepancy for $|V_{us}|$ opened
- Ab initio entering isospin breaking calculations
- New neutron results confirm (τ_n) and create new (λ) tensions

And several more are coming...

- Better lattice g_A probes ϵ_R (with new RC) + γW tests
- Mirrors can obtain equal V_{ud} footing with n, superallowed $\rightarrow$ independently test corrections

Atomic gains: EC/β^+ has very high b_F sensitivity & measuring atomic exchange necessary for DM & ALP searches

Thank you!

NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

fwo