V_{ud}: Recent theoretical progress and experimental opportunities

Leendert Hayen

V_{ud} workshop GANIL

5 November 2024

RÉGION NORMANDIE

lpc Caen

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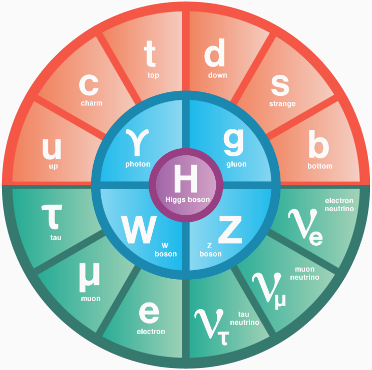
Meet the Standard Model

Three out of four
fundamental forces (no gravity):

Standard Model



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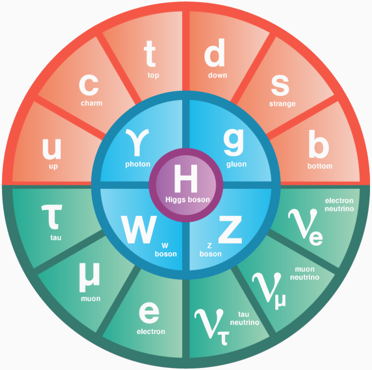

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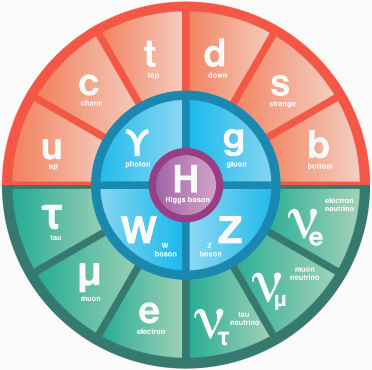

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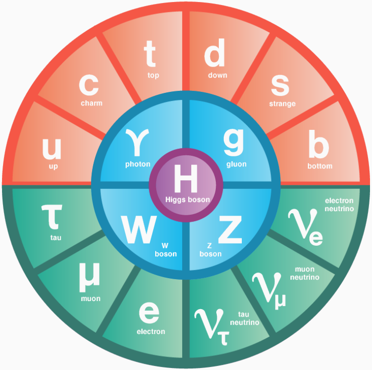
Open questions: dark matter, gravity, neutrino masses, ...



Introduction: Standard Model

What to do?

SM tests @ low energy: sensitive to off-shell exotic physics
(footprints rather than actual beast)

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

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- (C)P violation
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Today: CKM unitarity

Introduction: Weak interaction & CKM matrix

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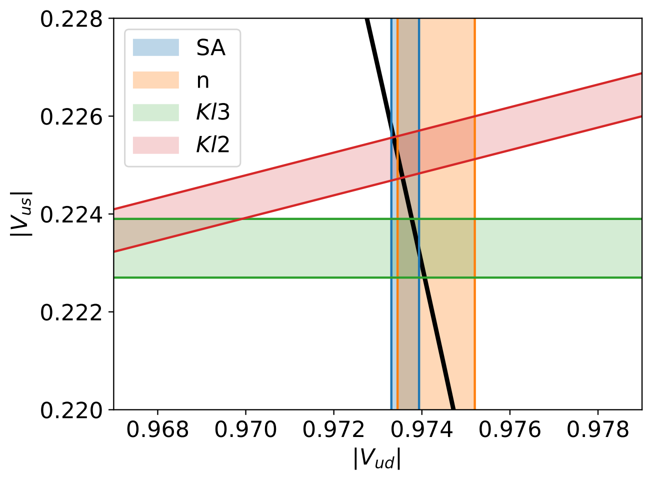
(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

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'



What would new physics look like?

SM has V-A structure, but more generally

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

at the quark level

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at the quark level

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

CKM unitarity: V_{ud}

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

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Semi-leptonic up-down decay rate

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

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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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Master formula

$$ft(1 + \delta'_R)(1 + \Delta_R^V)(1 + \delta_{NS} - \delta_C) = \frac{K}{G_F^2 V_{ud}^2 M_{\text{tree}}^2}$$

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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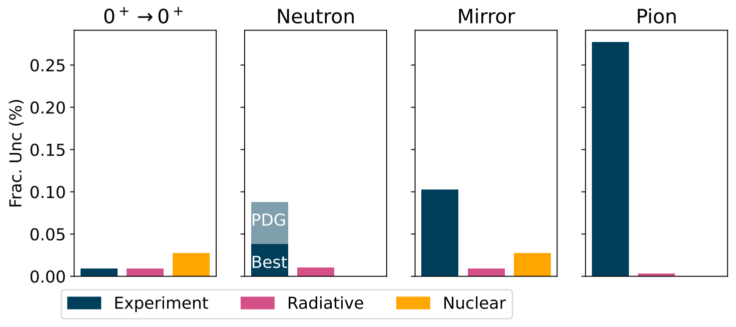

$\pi^+ \rightarrow \pi^0 e^+ \nu_e$ very hard (BR $\sim 10^{-8}$), SA new nuclear corrections!

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Nuclear sandbox → make hadronic theory easy

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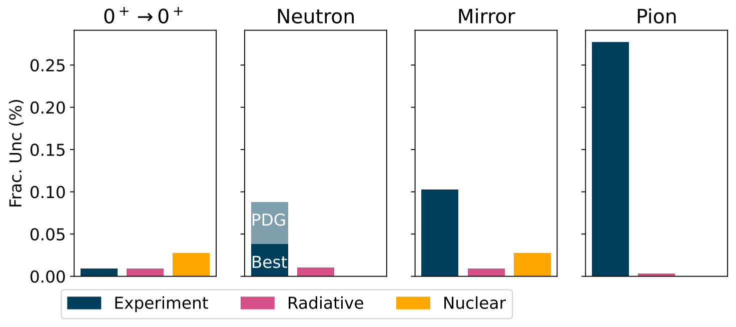

Status of $0^+ \to 0^+$ **great nuclear structure triumph**

LH, ARNPS 74 (2024) 497

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Theory changes overview

Recall master equation:

$$ft(1+\delta_R')(1+\Delta_R^V)(1+\delta_{NS}-\delta_C) = \frac{K}{G_F^2 V_{ud}^2 M_{\text{tree}}^2}$$

Every element has received updates/overhauls.

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Separate into tree level & loop level

Summary:

- δ_C: Isospin symmetry breaking of M_F
- f: phase space factor
- δ'_R: 'outer' radiative corrections
- Δ^V_R: single-nucleon 'inner' radiative corrections
- δ_{NS}: Changes in Δ^V_R due to nuclear structure

All except for Δ^V_R are **open questions** to this day!

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Summary *of changes*:

- δ_C: Ab initio & data-driven methods
- f: weak radii & Fermi function
- δ_R': RGE methods find differences in $\mathcal{O}(\alpha^2 Z^3)$ and beyond
- Δ_R^V: Dispersion and lattice QCD confirm 'inner' RC change
- δ_{NS}: Focus on coherent quasielastic nuclear response

All except for Δ_R^V are **open questions** to this day!

Isospin breaking updates

Isospin breaking ($\sim$Coulomb interaction) means

$$M_F^2 = (M_F^0)^2(1 - \delta_C)$$

with $\delta_C \sim 0.1 - 1\%$ for **nuclei**.

Isospin breaking updates

Isospin breaking ($\sim$Coulomb interaction) means

$$M_F^2 = (M_F^0)^2(1-\delta_C)$$

with $\delta_C \sim 0.1-1\%$ for **nuclei**. Traditional approaches separate into

- δ_{C1}: isospin-mixing meaning $\langle\pi|a_{p,\alpha}|\phi_i\rangle^* \neq \langle\phi_f|a^\dagger_{n,\alpha}|\pi\rangle$
- δ_{C2}: radial mismatch, i.e. proton and neutron orbits are not the same

but conceptual issues already noted 15 years ago (Miller & Schwenk)

See talk by N. Smirnova

Isospin breaking updates

New proposal to use charge radii & ab initio theory. May write

$$\delta_C \simeq \sum_{T=0,1,2} \frac{\langle a; T || V_{\mathrm{ISB}} || g; 1 \rangle^2}{(E_{a,T} - E_{g,1})^2}$$

over all states a and ground state g, **assuming** V_{ISB} is isovector.

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See talk by Michael Heines

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See talk by Michael Heines

Interesting development: In *single nucleon*, ISB was assumed negligible ($\delta_C \sim (m_u - m_d)^2/\Lambda^2_{\mathrm{QCD}}$), but recently challenged and can be $\mathcal{O}(10^{-4})$!

PLB 838 (2023) 137654; PLB 846 (2023) 138259

Phase space updates

Integrating over β spectrum in usual expression

$$f = m_e^{-5} \int_{m_e}^{E_0} dE \; pE(E_0 - E)^2 F(Z,E) C(Z,E) K(Z,E)$$

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$$f = m_e^{-5} \int_{m_e}^{E_0} dE\ pE(E_0 - E)^2 F(Z,E) C(Z,E) K(Z,E)$$

but contains subtleties

- Depends on nuclear wave functions in $C(Z,E) \rightarrow$ weak charge density ρ_{cw}
- Special place for Fermi function $F(Z,E) \rightarrow$ is this a nice QFT object?

First point was long known (C_I in Wilkinson, shell model in H&T), but model-dependent. Data-driven treatment using charge radii

$$\rho_{\mathrm{cw}} = \rho_{\mathrm{ch},0} + \frac{Z_{-1}}{2}(\rho_{\mathrm{ch},-1} - \rho_{\mathrm{ch},1})$$

uncertainties $\mathcal{O}(10^{-3-4})$

Seng & Gorchtein, PRC 109 045501 (2024)

Phase space and δ'_R updates

Special place of Fermi function is artefact of traditional segmented calculations (actually long-wavelength photon exchange)

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$F(Z, E)$ probes $e^{\pm}$ density at $r = 0$, but since solution $\rightarrow \infty$, introduce UV cutoff *avant la lettre*: R, the nuclear radius.

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Currently called into question: is $F(Z, E)$ a good QFT object? When including higher-order corrections ($F \to F(1 + \delta_R)$), things become more complicated.

Still an **open question**, confusion due to disagreements with older calculations (1980's Jaus & Rasche)

PRL 133, 021803 (2024), PRD 109, 056006 (2024), PRD 108 (2023) 053003

Δ_R updates

Loop contribution that is ($\sim$)solved: Δ_R^V

Single-nucleon RC in β-decay can ($\sim$) be separated into

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

Δ_R updates

Loop contribution that is (~)solved: Δ_R^V

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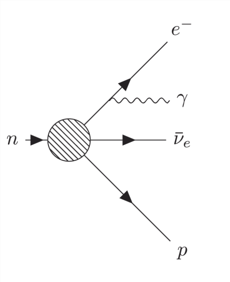
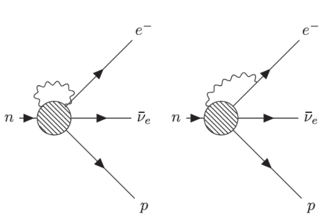
δ_R mainly originates from real photon emission



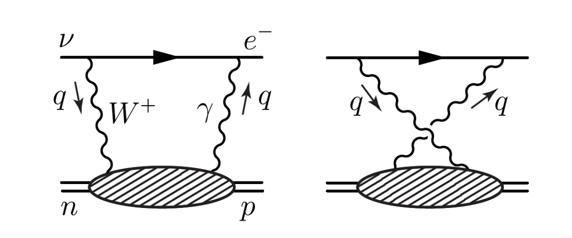
$\Delta_R^{V,A}$ renormalizes $g_{V,A}$

$$g_i^2 \to g_i^2(1 + \Delta_R^i)$$



Recent changes: Δ_R^V

The culprit for Δ_R^V: famous γW box



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

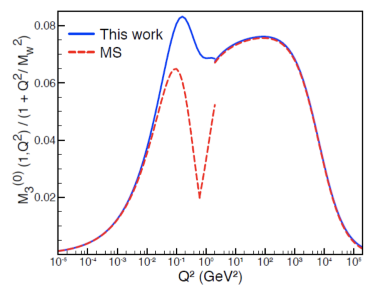
Recent changes: Δ_R^V

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

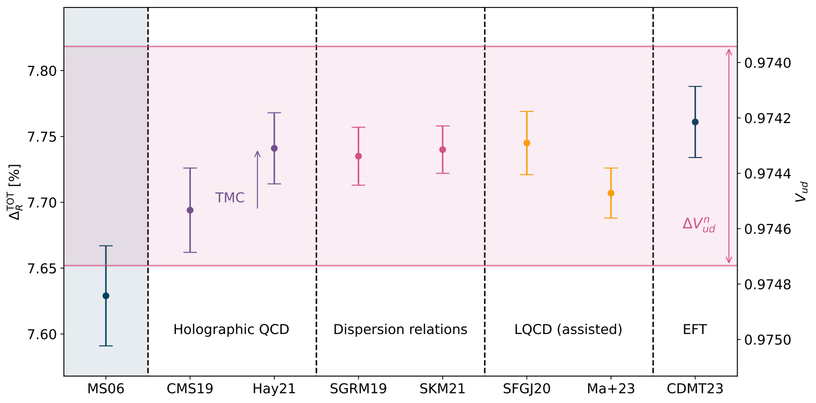
Beginning of our CKM debacle!



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

Δ_R^V updates

Number of different calculations performed, convergence

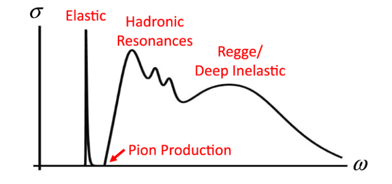


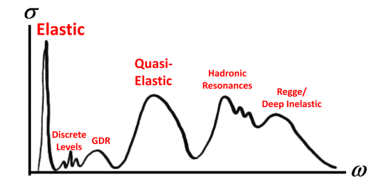
Small differences remain, neutron experimental uncertainty too large to distinguish

LH, ARNPS 74 (2024) 497

δ_{NS}: status 2018

Nuclear medium changes nuclear response, but also spectrum





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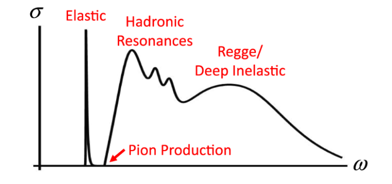
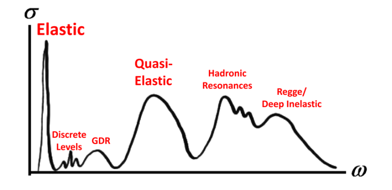




Paradigm shift in analysis, two major effects

Quasi-elastic contributions

$$\delta_{NS}^{A} = \frac{\alpha}{\pi}[-0.47 \pm 0.14]^{\mathrm{QE}}$$

Estimated using free Fermi gas

Nuclear polarization

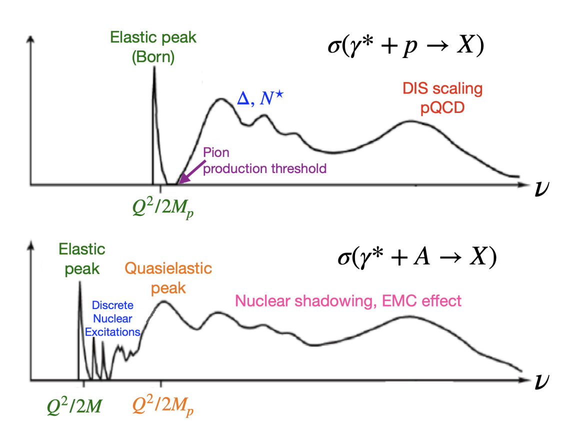
$$\delta_{NS}^{A}(E) \sim (1.6 \pm 1.6) \times 10^{-4} \left(\frac{E}{\mathrm{MeV}}\right)$$

Current $0^+ \to 0^+$ bottleneck

Seng et al., PRD 100 013001

Current status on δ_{NS}

More sophisticated picture, first ab initio calculations emerging (See talk by Mehdi Drissi)



Energy-dependent effects might be detectable, **nuclear** shadowing effects largely unknown Seng, Gorchtein ARNPS 74 (2024) 1

Open questions for mirror δ_{NS}

Situation is analogues but **more complicated** than $0^+ \to 0^+$.
Significant questions on:

- How do energy-dependent terms enter for axial transitions?
- What about nuclear shadowing for spin-dependent transitions?

Mirror decays extract $\rho = g_A M_{GT}/g_V M_F$ from angular correlations ($a_{\beta\nu}$, A_β), but both effects may mean $\rho^{\mathrm{corr}} \neq \rho^{\mathrm{Ft}}$.

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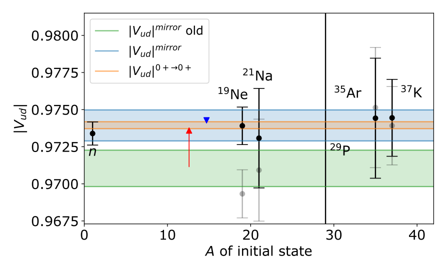
Happened before: double counting was resolved and V_{ud}^{mirror} now agrees with $V_{ud}^{0^+\to 0^+}$

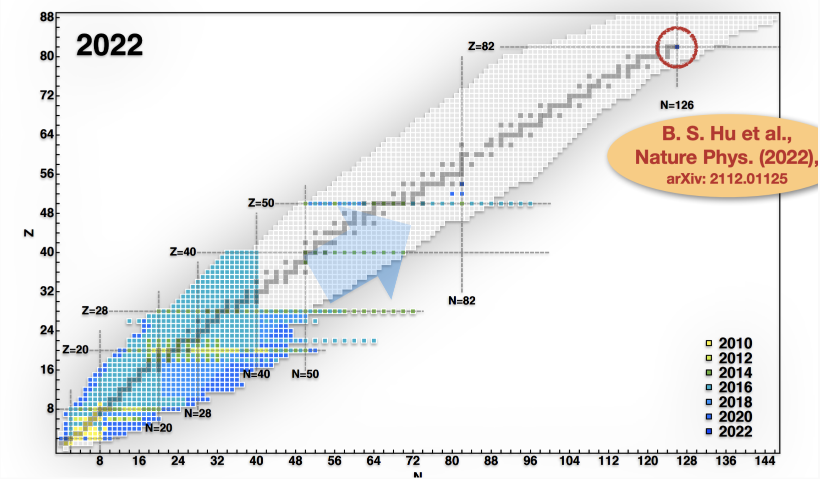
LH, PRD 103, 113001;

LH, ARNPS 74 (2024) 497



Progress in nuclear ab initio theory

Field is charging full steam ahead on nuclear ab initio



H. Hergert, Frontiers in Physics (2020)

Theory summary

Takeaways

- Paradigm shift in radiative corrections started CAA, converged for Δ_R^V

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Now, let's talk experiment

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Overview experimental opportunities

Several science drivers in parallel

- New experimental techniques to sidestep common systematics
- Spectrum shape measurements for δ_{NS} validation
- Precision measurements on low-mass isotopes for nuclear ab initio ladder benchmark

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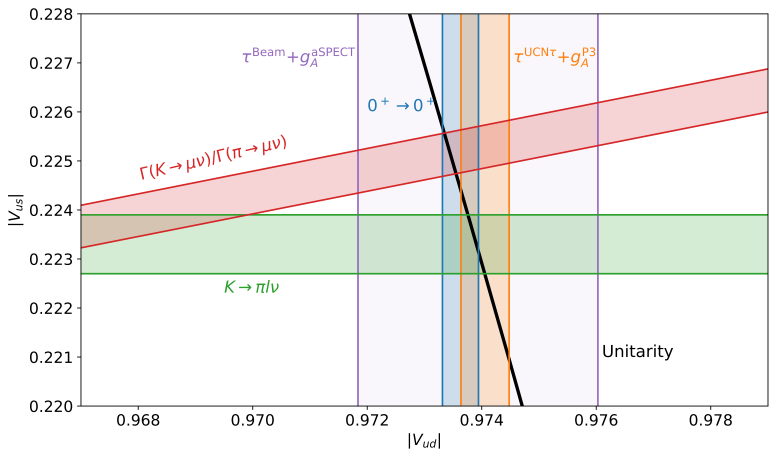
Necessary push in neutrons, opportunities in mirrors, validation in superalloweds

Progress in neutron experiments

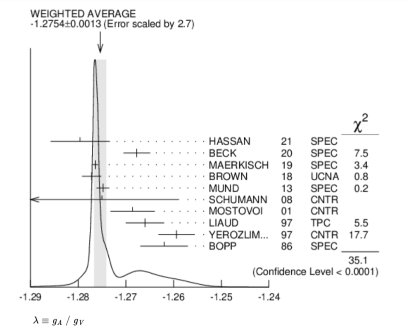
Situation is complicated in both τ_n and $\lambda = g_A/g_V$ determinations

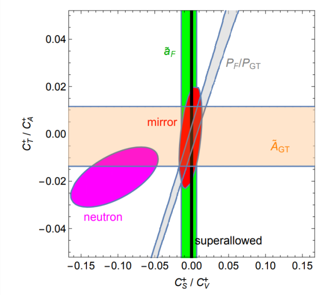


'Outlier' measurements agree with most precise for CKM unitarity

Status on λ

Current PDG average



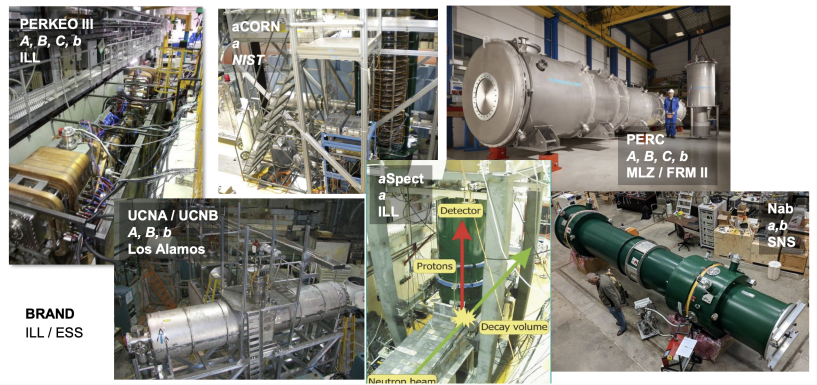


aSPECT ($a_{\beta\nu}$) is in tension with other recent measurements (A_β)

Falkowski et al., JHEP04(2021)126

Progress in neutron experiments

Several campaigns worldwide (see talk by Bastian Märkisch)

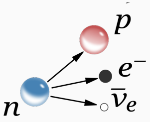


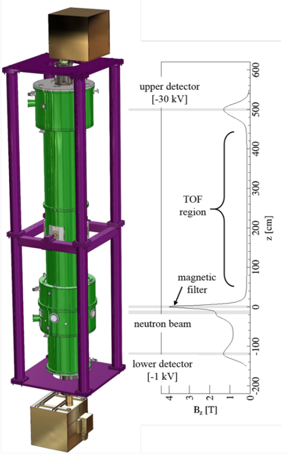
Nab is only $a_{\beta\nu}$ experiment aiming at 0.1%, **crucial input**

Measurement of β-ν angular correlation

$$d\Gamma \propto d\Gamma_0 \left[1 + a_{\beta\nu} \beta \hat{p}_e \cdot \hat{p}_\nu\right]$$

in **neutron** β **decay** @ SNS (ORNL)





Nab - overview

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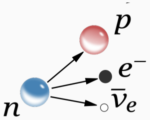
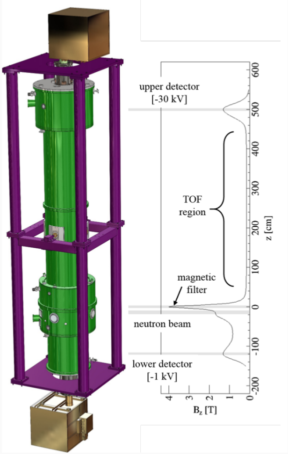
$$d\Gamma \propto d\Gamma_0 \left[1 + a_{\beta\nu} \beta \hat{p}_e \cdot \hat{p}_\nu\right]$$

in **neutron** β **decay** @ SNS (ORNL)





To leading order in SM

$$a_{\beta\nu} = \frac{1 - g_A^2}{1 + 3g_A^2}$$

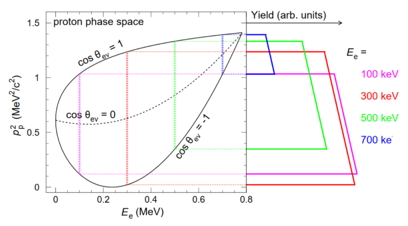
and

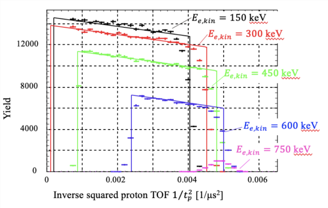
$$\frac{\delta a}{a} \approx 5 \frac{\delta g_A}{g_A}$$

meaning factor 5 sensitivity enhancement!

Nab progress

Measure p^+ instead of ν, $\vec{p}_p = -(\vec{p}_e + \vec{p}_\nu)$





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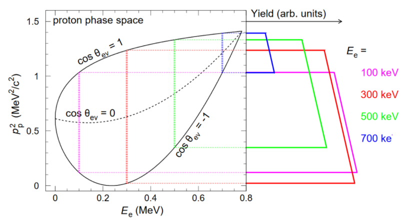
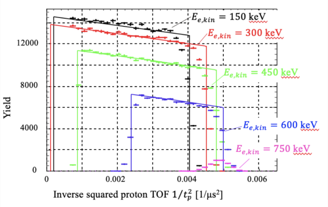
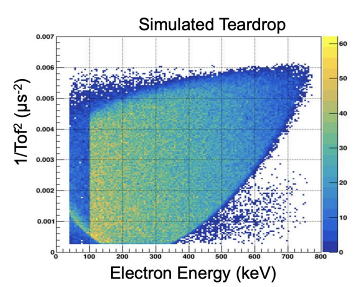
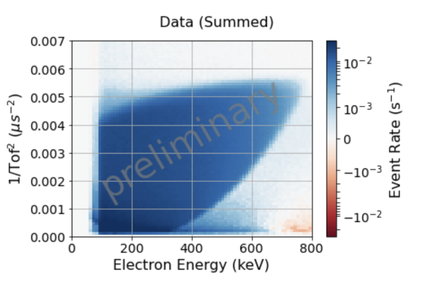




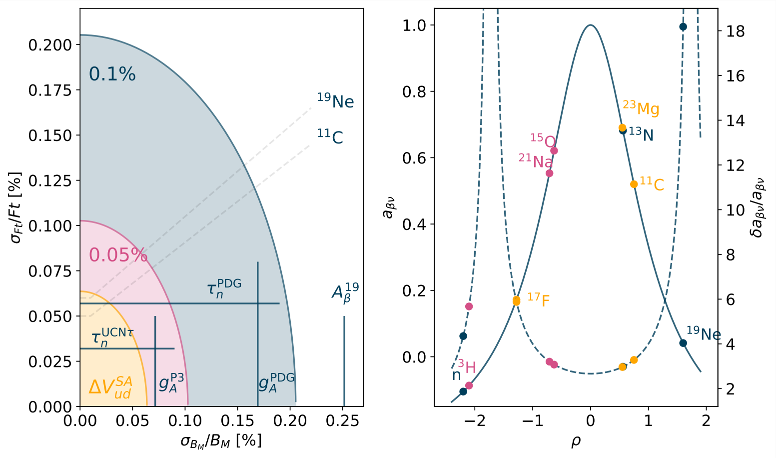
First physics runs at ORNL are promising!





Sensitivity enhancement in mirror transitions

Several mirror isotopes have well-known ft values to rival SA



Strong enhancements depending on the system

LH, ARNPS 74 (2024) 497

Experimental innovation

Community is investi(gati)ng in different ideas

with **new spectroscopy techniques** & traps

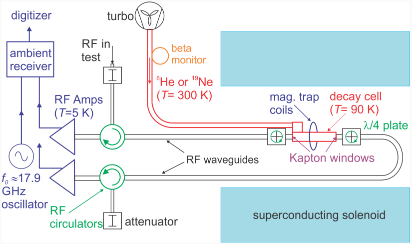
with additional great progress in the $A = 8$ system

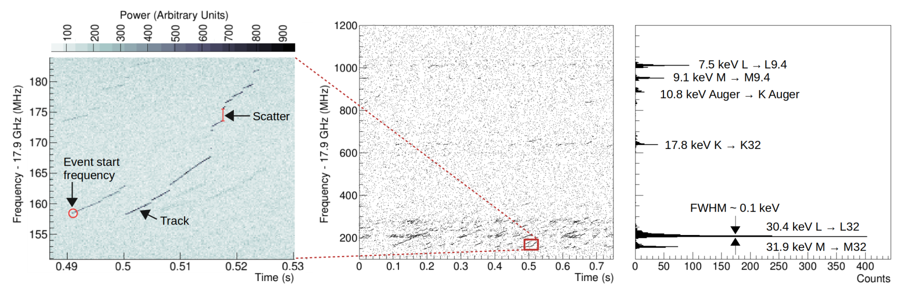
New technology: CRES

Cyclotron Radiation Emission Spectroscopy

$$f = \frac{|q|}{2\pi} \frac{B}{m_e + E_{kin}}$$

^{6}He and ^{19}Ne

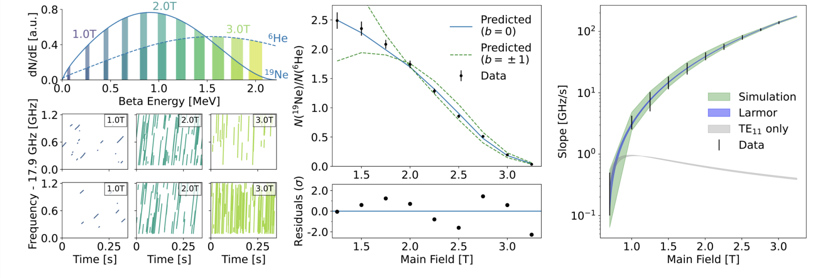




Physical Review Letters 131 (2023), 082502

New technology: CRES

Use ratio method: ^{6}He and ^{19}Ne have opposite b_F sign

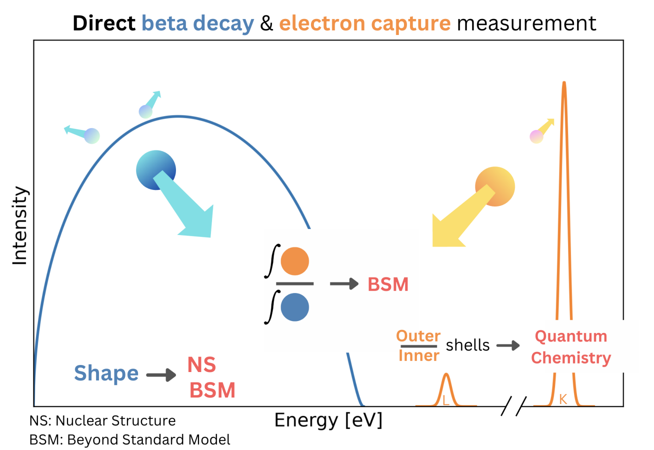


Ratio means many systematic effects cancel to first order

Physical Review Letters 131 (2023), 082502

Direct recoil spectroscopy

Richness in pure recoil spectra, but experimentally very difficult!



Enabled by novel superconducting tunnel junctions

SALER@FRIB: First STJ online measurements

SALER @ FRIB

- Acceptance testing complete
- Commissioning started
- Will continue through 2024

U.S. DEPARTMENT OF ENERGY | Office of Science

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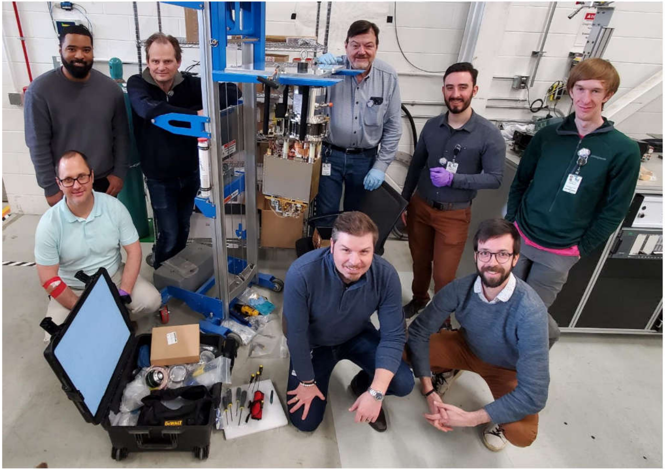
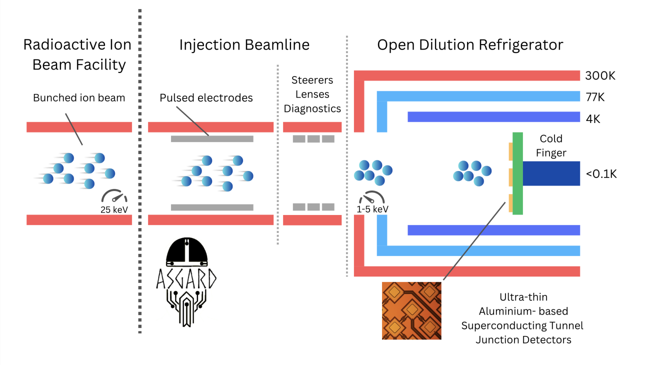
FRIB



ASGARD

Open STJs up to all ISOL beams, **precision spectroscopy**



RÉGION NORMANDIE

European Research Council
Established by the European Commission

Reduce systematic effects by 2-3 orders of magnitude!

(See talk by Mohamad Kanafani)

Table of Contents

Summary & Outlook

Theory very active, all inputs are being reevaluated. Significant opportunities/challenges for nuclear ab initio

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Experimentally, neutron has made great progress but more input is crucial. Mirror isotopes continue to be promising due to large enhancements

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Theory very active, all inputs are being reevaluated. Significant opportunities/challenges for nuclear ab initio

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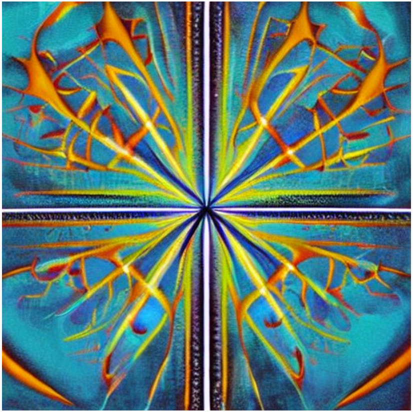
Experimentally, neutron has made great progress but more input is crucial. Mirror isotopes continue to be promising due to large enhancements

New spectroscopy techniques incoming, recoil spectroscopy with quantum sensors is highly promising!

Thank you!



β decay symmetries according to Stable Diffusion

Aside: recent progress on Δ_R^A

First $\mathcal{O}(\alpha)$ calculation of Δ_R^A, follow-up with dispersion relations and lattice QCD

$$\Delta_R^A - \Delta_R^V = 0.13(13) \times 10^{-3}$$

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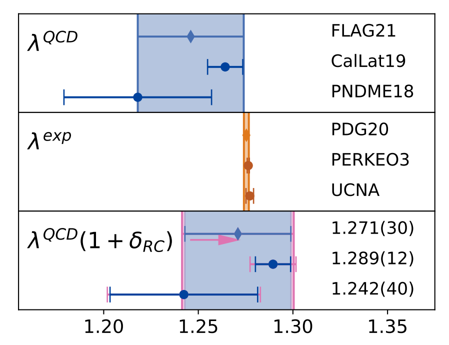
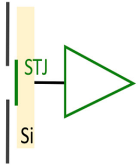
$$\Delta_R^A - \Delta_R^V = 0.13(13) \times 10^{-3}$$

but only first half of the story... also here large ISB effects



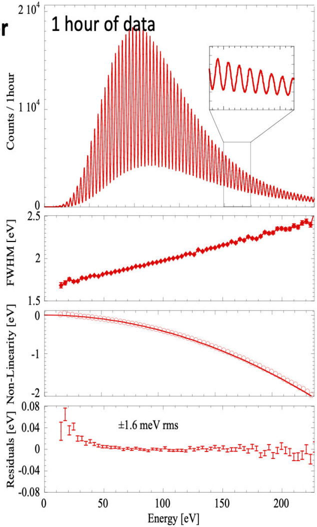
First time: $\delta_{\rm RC}^{(\lambda)} \in \{1.4, 2.6\} \cdot 10^{-2}$ LH, PRD 103 113001; Seng, Particles 2021, 397; Gorchtein & Seng, JHEP 10 53; PRL 129 121801

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)

The BeEST experiment (Slide by Kyle Leach)

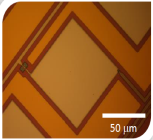
TRIUMF

Rare-isotope implantation at TRIUMF-ISAC

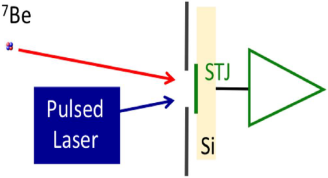
THE BeEST

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



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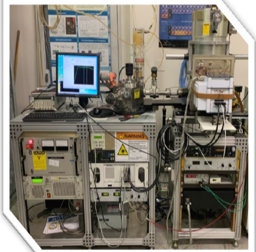
EMPIR EURAMET

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



Lawrence Livermore National Laboratory

Introduction: Weak interaction & CKM matrix

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

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

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Unitarity requires

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

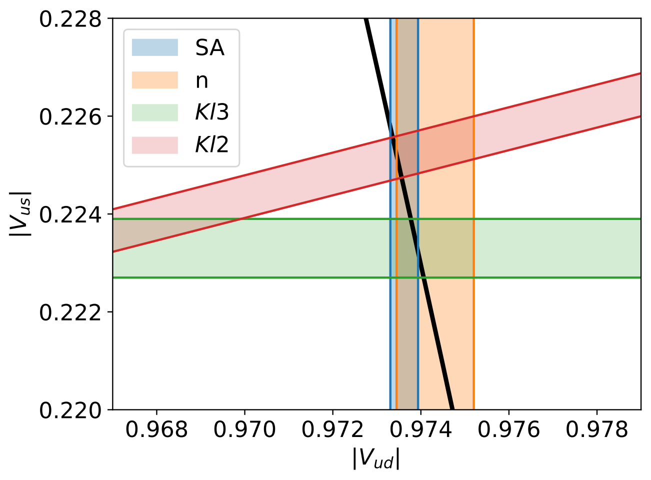
(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

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

CKM unitarity: Current status

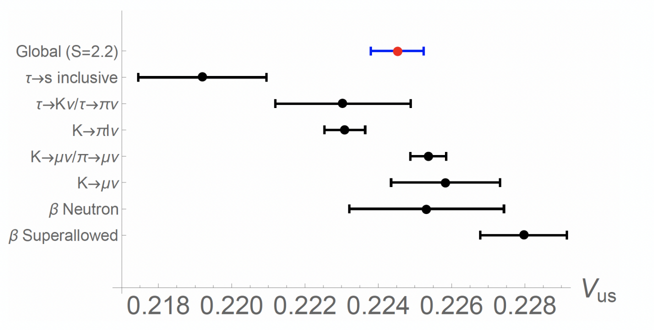
Signs of non-unitarity at few σ level...

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



CKM unitarity: Cabibbo Angle Anomaly

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



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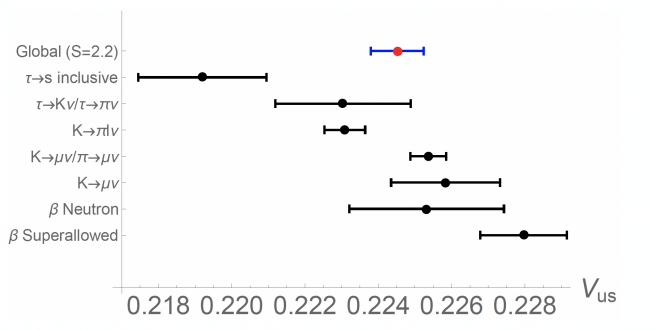

Takeaways assuming Standard Model physics:

- 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

Exotic contributions

A more modern way of interpreting BSM physics

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Effective field theory: new physics at scale $\Lambda_{BSM} \gg$ LHC

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i=1} c_i \frac{\mathcal{O}_{4+i}}{\Lambda^i_{BSM}}$$

effective operators $\mathcal{O}(i)$. Expansion in parameter $c_i/\Lambda^i_{BSM} \ll 1$

Exotic contributions

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effective operators $\mathcal{O}(i)$. Expansion in parameter $c_i/\Lambda^i_{BSM} \ll 1$

Phenomenological theories will give different $\{c_i\}$,

but agnostic experimental analysis

Effective β decay

SM has V-A structure, but more generally

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

at the quark level

Effective β decay

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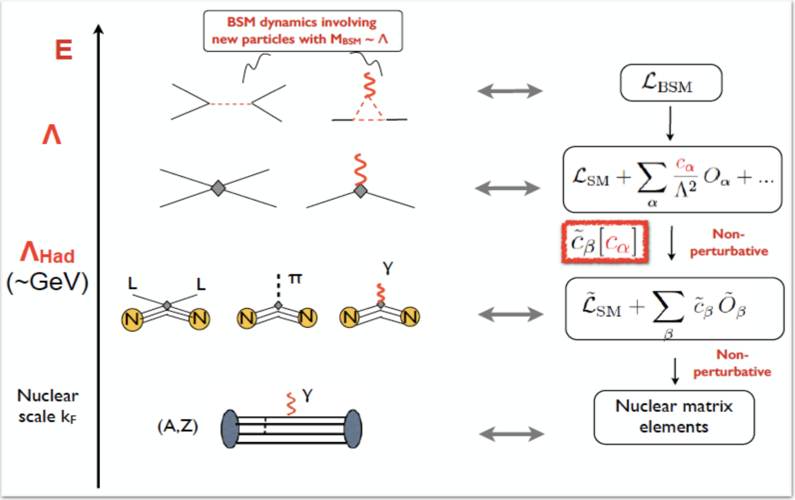
at the quark level

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

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

Effective field theory tower Slide by V. Cirigliano



Chiral EFT, Lattice QCD

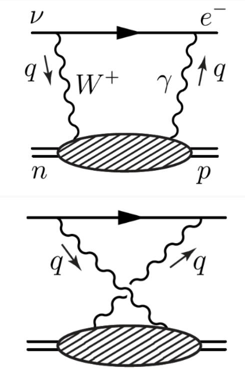
Nuclear many-body methods

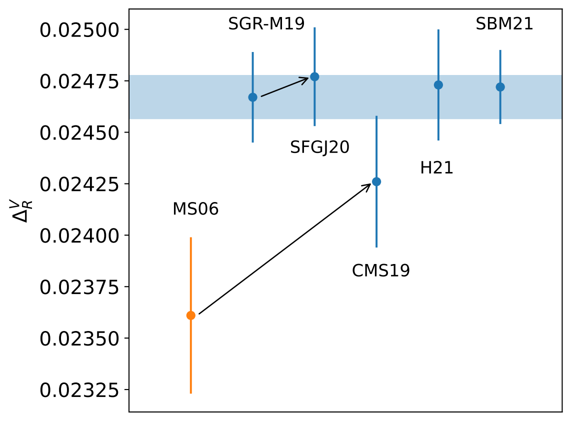
Effective field theory recipe Slide by V. Cirigliano

- In order to build L_{eff}, one needs to specify:
  - ★ Relevant low-E degrees of freedom: *assume* SM field content
    - ★ One Higgs doublet, no light ν_R and no other light fields
  - ★ Symmetries: L_{eff} must reflect symmetries of underlying theory
    - ★ Assume underlying theory respects SM gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$
    - ★ But not necessarily SM symmetries that result from keeping only terms of dimension ≤ 4
  - ★ Power counting in E/Λ, $v_{EW}/\Lambda \ll 1$ (recall $v_{EW} = G_F^{-1/2}$): organize analysis in terms of operators of increasing dimension (5,6,...)

Recent changes: Δ_R^V

Number of new calculations performed





Now good convergence: uncertainty halved but about 3σ shift

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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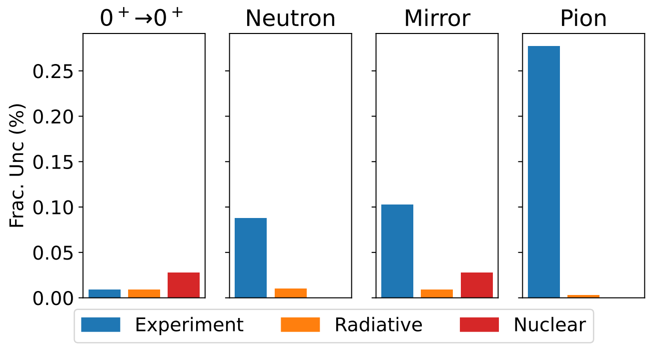
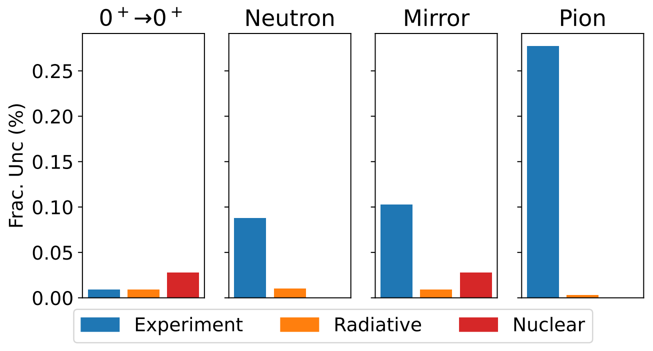


$\pi^+ \rightarrow \pi^0 e^+ \nu_e$ very hard (BR $\sim 10^{-8}$), SA new nuclear corrections!

CKM unitarity: V_{ud} precision

Nuclear sandbox → make hadronic theory easy

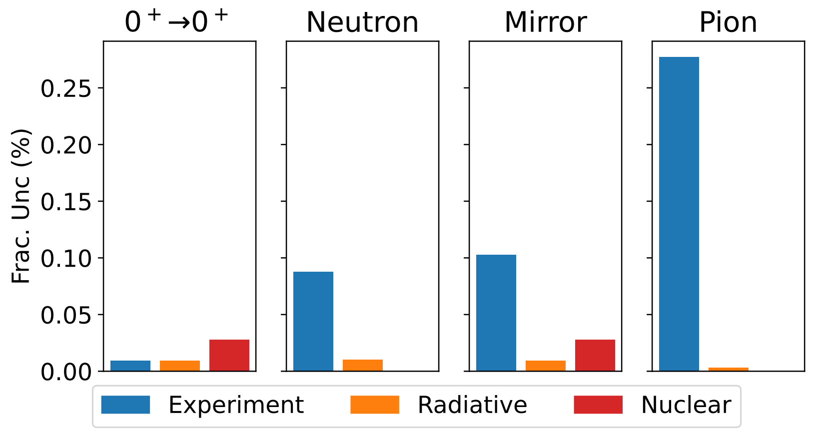
- Pion
- Neutron
- Superallowed $0^+ \to 0^+$
- $T = 1/2$ mirrors



Status of $0^+ \to 0^+$ **great nuclear structure triumph**

CKM unitarity: V_{ud} precision

Four ($\sim$)competitive channels of extracting V_{ud}

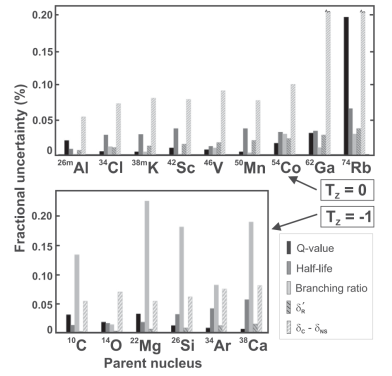


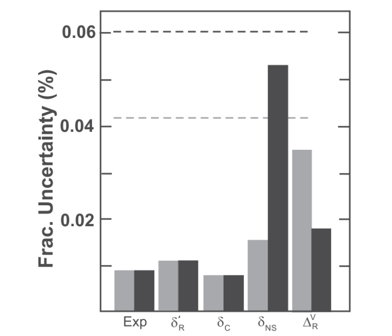
Status of $0^+ \to 0^+$ **great nuclear structure triumph**

2018-2020 reanalysis nuclear structure current bottleneck

Superallowed uncertainties

Experimentally, $T_z = -1$ limited by BR (new ^{10}C welcome)





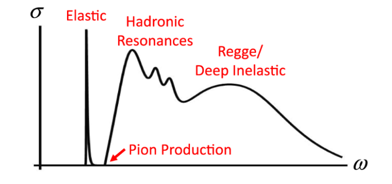
Moving towards mature *ab initio* theory evaluation

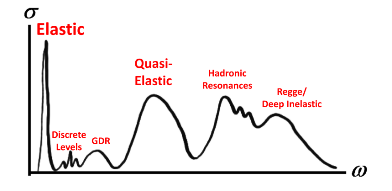
Talk by Bertram Blank

Hardy & Towner PRC 102 (2020) 045501

Recent changes: δ_{NS}

Nuclear medium changes nuclear response, but also spectrum





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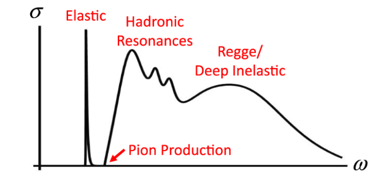

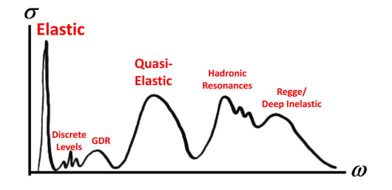

Paradigm shift in analysis, two major effects

Quasi-elastic contributions

$$\delta_{NS}^{A} = \frac{\alpha}{\pi}[-0.47 \pm 0.14]^{\mathrm{QE}}$$

Estimated using free Fermi gas

Nuclear polarization

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

Current $0^+ \to 0^+$ **bottleneck**

Seng et al., PRD 100 013001

On the radar: 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)

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

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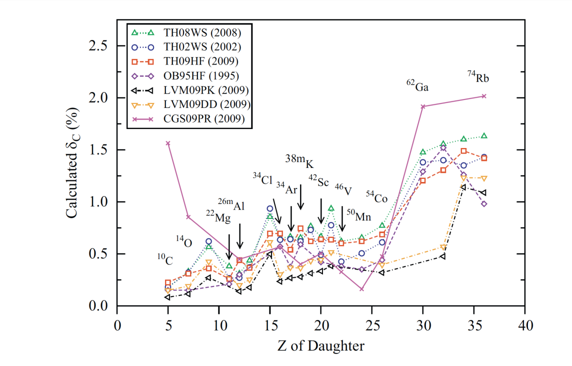
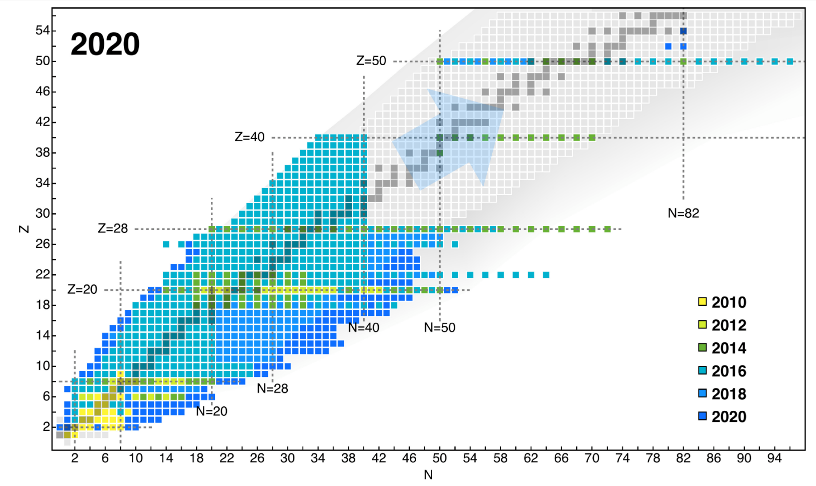


Grinyer et al., NIMA 622 (2010) 236

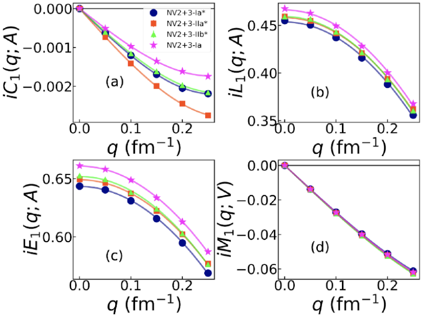
Progress in nuclear ab initio theory



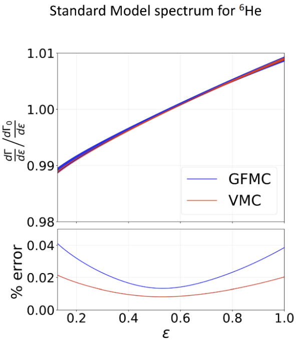
H. Hergert, Frontiers in Physics (2020)

Ab initio is providing bottleneck input for spectral measurements

Beta Decay Spectrum



Dominant terms $L_1^{(0)}$ and $E_1^{(0)}$ have model dependence of ~1% to ~2%



$\varepsilon = \frac{E_e}{\omega}$

τ_{GFMC} = 808 +/- 24 ms

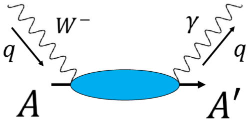
$\tau_{Expt.}$ = 807.25 +/- 0.16 +/- 0.11 ms

Garrett King et al. arXiv:2207.11179

Looking at implementing δ_{NS} for ^{10}C

No Core Shell Model (Slide by Michael Gennari)

Compton amplitude in the NCSM



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- Nuclear matrix elements for γW-box
  1) Express currents in momentum space
  2) Multipole expansion of current operators
  3) Connect currents to effective one–body operators

Lanczos continued fractions method to compute Green's functions!

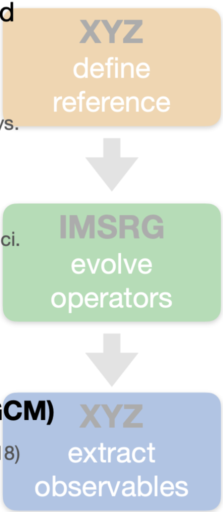
$$T_3(q_0, Q^2) = -4\pi i \frac{q_0}{q} \sqrt{M_i M_f} \sum_{J=1}^{\infty} (2J+1)$$

$$\times \langle A\lambda_f J_f M_f | \Big[T^{mag}_{J0}(q) G(M_f + q_0 + i\epsilon) T^{5,el}_{J0}(q) + T^{el}_{J0}(q) G(M_f + q_0 + i\epsilon) T^{5,mag}_{J0}(q)$$

$$+ T^{5,mag}_{J0}(q) G(M_i - q_0 + i\epsilon) T^{el}_{J0}(q) + T^{5,el}_{J0}(q) G(M_i - q_0 + i\epsilon) T^{mag}_{J0}(q) \Big] | A\lambda_i J_i M_i \rangle$$

Going heavier: IM-SRG type methods (Slide by Heiko Hergert)

- IMSRG for closed and open-shell nuclei: IM-HF and IM-PHFB
  - HH, Phys. Scripta, Phys. Scripta 92, 023002 (2017)
  - HH, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tuskiyama, Phys. Rept. 621, 165 (2016)
- **Valence-Space IMSRG (VS-IMSRG)**
  - S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. Rev. Nucl. Part. Sci. **69**, 165
- In-Medium No Core Shell Model (IM-NCSM)
  - E. Gebrerufael, K. Vobig, HH, R. Roth, PRL **118**, 152503
- **In-Medium Generator Coordinate Method (IM-GCM)**
  - J. M. Yao, J. Engel, L. J. Wang, C. F. Jiao, HH PRC 98, 054311 (2018)
  - J. M. Yao et al., PRL 124, 232501 (2020)



+ Coupled Cluster, . . .

Nuclear theory impact

Major advances in last decade, EFT come into its own

Quantifiable theory uncertainties are game-changer for precision
FS: paradigm shifts are strong driver of progress in the field

Benefit from 'rigorous' theory overlap at low masses (NCSM, GFMC, QMC)

- $0^+ \rightarrow 0^+$:^{10}C & ^{14}O
- Promising isotopes: ^{6}He, ^{11}C, ...

to confidently go higher (CC, IM-SRG, IM-GCM, ...)

Path forward for $0^+ \rightarrow 0^+$ V_{ud}

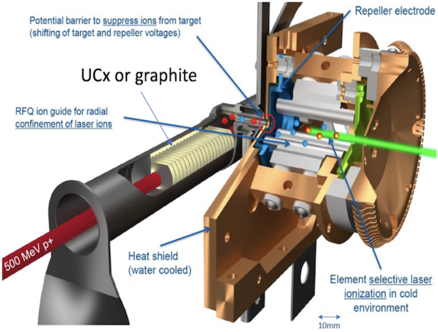
BeEST implantation

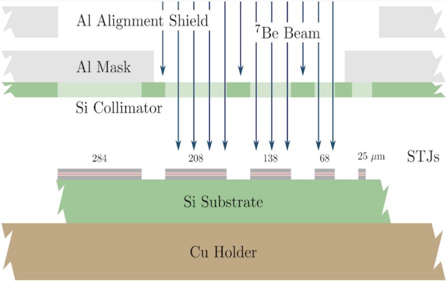
TRIUMF

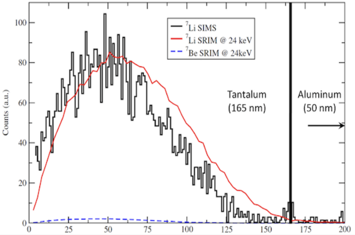
Isotope Separation On-Line (ISOL) Method

Element- and mass-selective delivery of ^{7}Be:

- Purity > 80%
- Rate > 1e8 pps

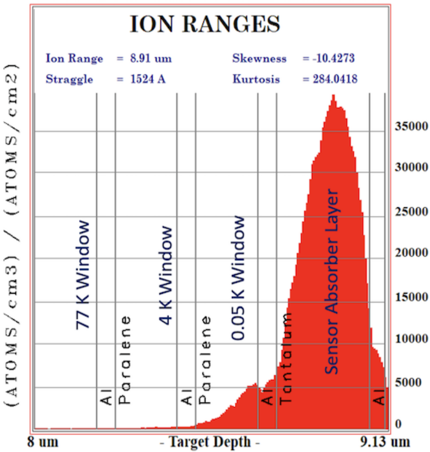






SALER implantation

11 MeV ^{11}C Beam w/ 8μm Al foil



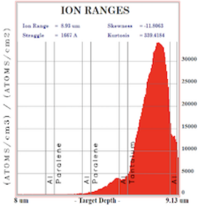
For a given energy, initial beam from ReA can be +/- a few % in spread

1% spread gives ~50 nm width in the depth profile

Total $^{11}C^{+}$ to achieve goal: ~10^7 (< 2 days of beam @ 100 pps)

Purity: 1 part in 10^6

11.1 MeV ^{11}C Beam



10.9 MeV ^{11}C Beam