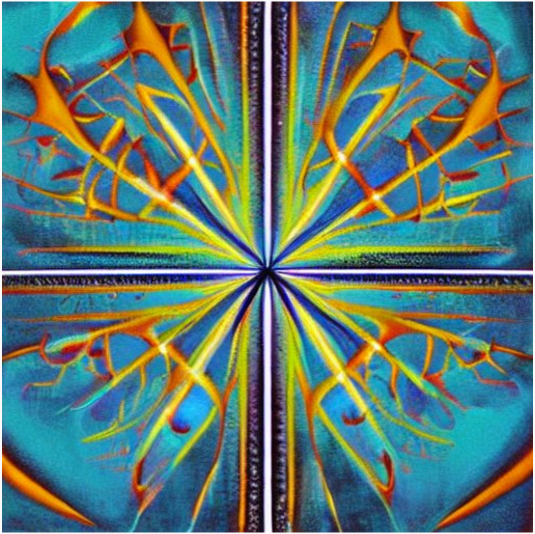
BSM physics searches using β decay

Leendert Hayen

NSAC Town Hall Meeting @ ANL, Nov 15 2022

NC State & TUNL, USA

β decay according to Stable Diffusion



Prompt: ‘beta decay symmetry as an oil painting’ on huggingface.co

β decay within fundamental symmetries

Many available observables & nuclei, energy scales from eV (recoil) to MeV (electrons, positrons)

β decay within fundamental symmetries

Many available observables & nuclei, energy scales from eV (recoil) to MeV (electrons, positrons)

SM has V-A structure, but more generally

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

at the quark level (+ sterile ν)

β decay within fundamental symmetries

Many available observables & nuclei, energy scales from eV (recoil) to MeV (electrons, positrons)

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

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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

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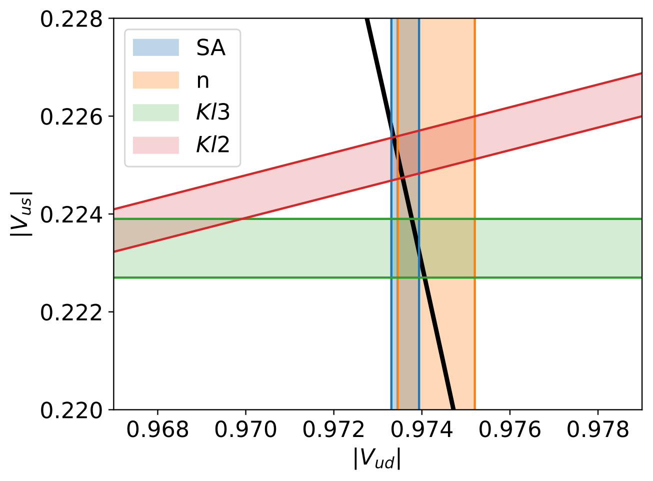
CKM unitarity: Current status

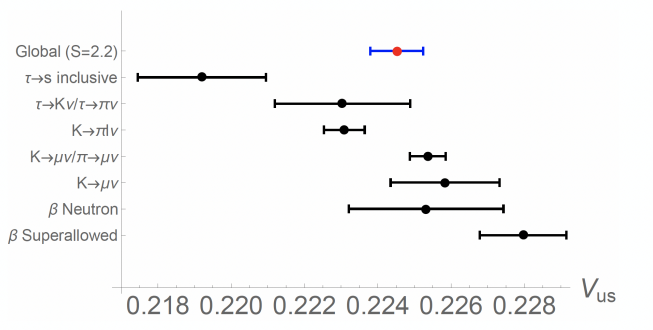
Signs of non-unitarity at few σ level...

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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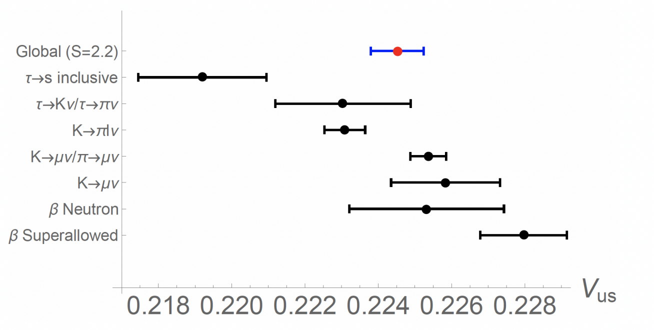
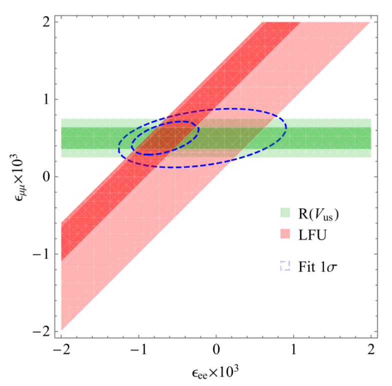


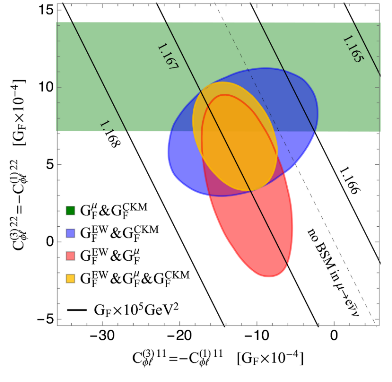
Takeaways assuming Standard Model physics:

- 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

CKM breadth

Interesting channel for LFU & SMEFT BSM searches



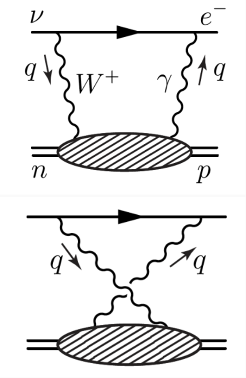


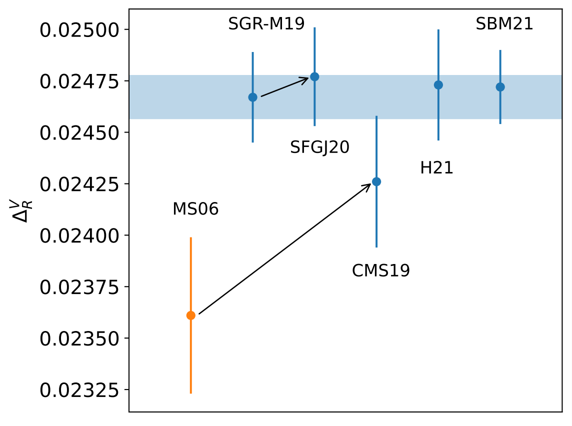
G_F from β decay belongs in precision electroweak fits!

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

Recent changes: Δ_R^V

Number of new calculations performed

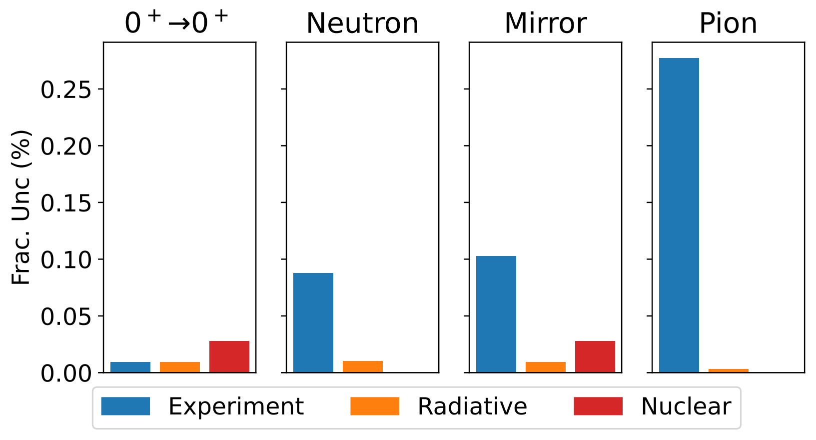




Now good convergence: uncertainty halved but about 3σ shift

CKM unitarity: V_{ud} precision

Four (~)competitive channels of extracting V_{ud}

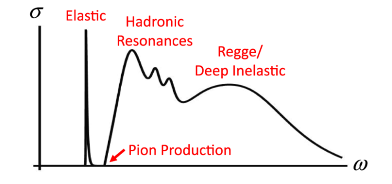


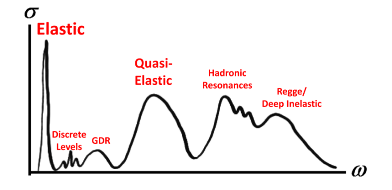
Status of $0^+ \to 0^+$ **great nuclear structure triumph**

2018-2020 reanalysis nuclear structure current bottleneck

Recent changes: δ_{NS}

Nuclear medium changes nuclear response, but also spectrum





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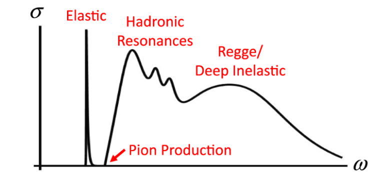

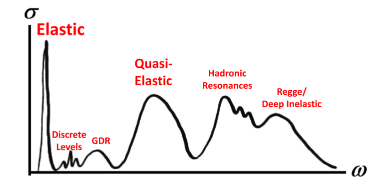

Paradigm shift in analysis, two major effects

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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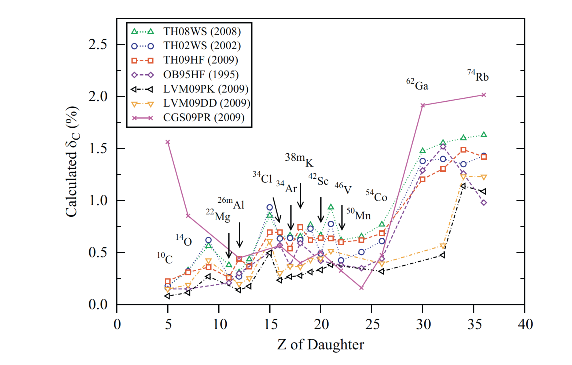
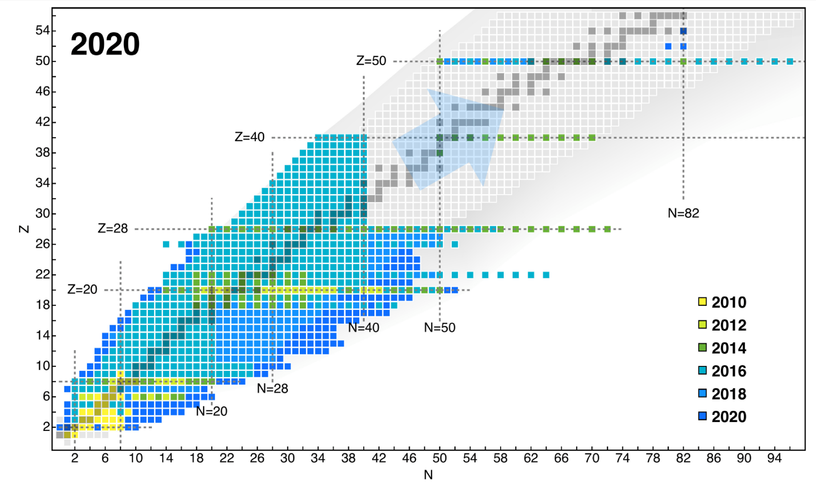


Grinyer et al., NIMA 622 (2010) 236

Progress in nuclear ab initio theory



H. Hergert, Frontiers in Physics (2020)

Nuclear theory impact

Major advances since last LRP, 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)

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

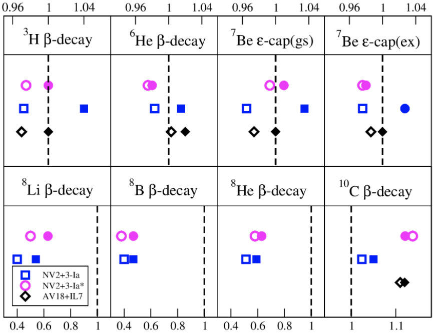
to confidently go higher (CC, IM-SRG, IM-GCM, ...)

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

Monte Carlo methods (Slide by Saori Pastore)

Low masses ($A < 12, 14$) are accessible to GFMC & QMC

Beta Decay and Electron Capture in Light Nuclei



Garrett King *et al.* PRC102(2020)025501

Calculations based on

- chiral interactions and currents
  NV2+3-Ia Norfolk unstarred
  NV2+3-Ia* Norfolk* starred
  Piarulli *et al.* PRL120(2018)052503
  Baroni *et al.* PRC98(2018)044003

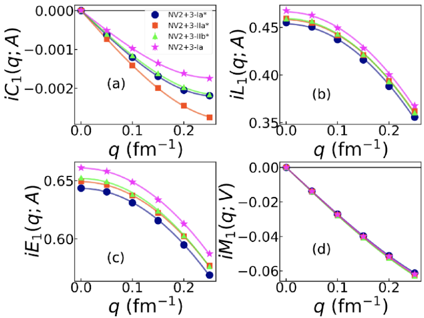
- phenomenological **AV18+IL7** potential and chiral axial currents (hybrid calculation)

Two-body currents are small/negligible;
Results for A=6-7 are within 2% of data;
Results for A=8 are off by a 30-40%;
Results for A=10 are affected by the second $J^\pi=(1^+)$ state in ^{10}B

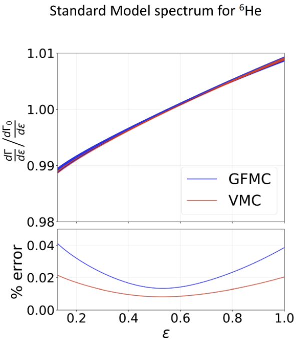
Monte Carlo methods (Slide by Saori Pastore)

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)

[8] Barrett et al. (2013) [11] Entem et al. (2017)
[9] Weinberg (1991) [12] Somà et al. (2020)
[10] Epelbaum (2009)

No–core shell model (NCSM)

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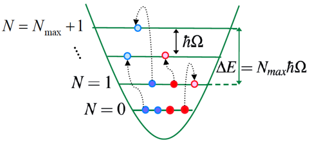
- *Ab initio* approach to many–body Schrödinger equation for bound states and narrow resonances **[8]**
- Nuclear interactions sole input **[9-10]**

$$H\left|\Psi_A^{J^\pi T}\right\rangle = E^{J^\pi T}\left|\Psi_A^{J^\pi T}\right\rangle$$

$$|\Psi_A^{J^\pi T}\rangle = \sum_{N=0}^{N_{max}} \sum_{\alpha} c_{N\alpha}^{J^\pi T} |\Phi_{N\alpha}^{J^\pi T}\rangle$$

Anti-symmetrized products of many-body HO states



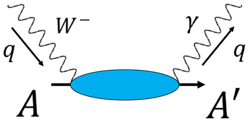
– Two body: NN-N^{4}LO(500) **[11]**
– Three body: 3N$_{\text{lnl}}$ **[12]**

Accessible transitions

^{10}C → ^{10}B and ^{14}O → ^{14}N

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

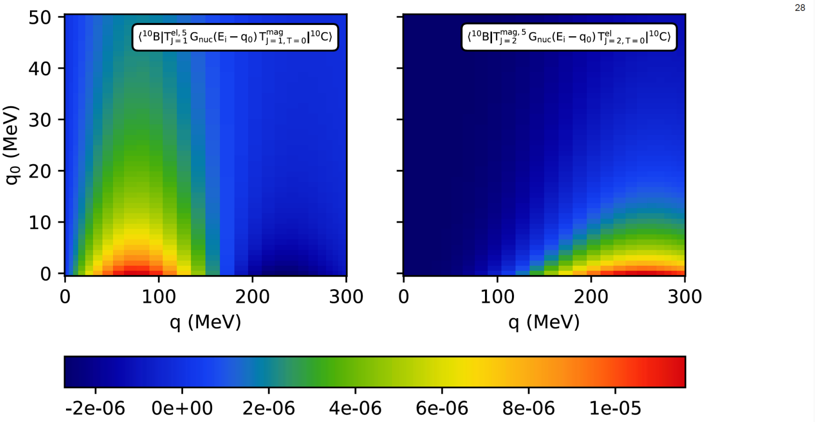
Lanczos continued fractions method to compute Green's functions!

$$T_3(q_0,Q^2) = -4\pi i \frac{q_0}{q}\sqrt{M_i M_f}\sum_{J=1}^{\infty}(2J+1)$$
$$\times \langle A\lambda_f J_f M_f| \Big[T_{J0}^{mag}(q)\, G(M_f+q_0+i\epsilon)\, T_{J0}^{5,el}(q) + T_{J0}^{el}(q)\, G(M_f+q_0+i\epsilon)\, T_{J0}^{5,mag}(q)$$
$$+ T_{J0}^{5,mag}(q)\, G(M_i-q_0+i\epsilon)\, T_{J0}^{el}(q) + T_{J0}^{5,el}(q)\, G(M_i-q_0+i\epsilon)\, T_{J0}^{mag}(q) \Big] |A\lambda_i J_i M_i\rangle$$

No Core Shell Model (Slide by Michael Gennari)

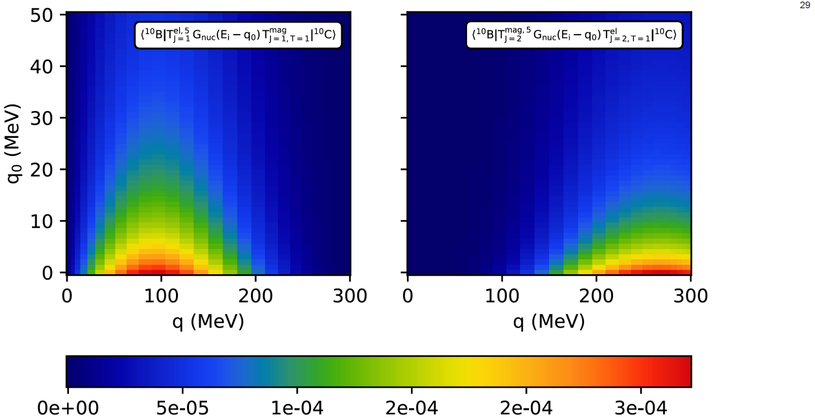
$G(M_i - q_0 + i\epsilon)$ terms: $T = 0$ EM current

Preliminary



No Core Shell Model (Slide by Michael Gennari)

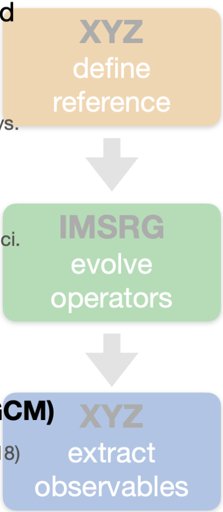
$G(M_i - q_0 + i\epsilon)$ terms: $T = 1$ EM current **Preliminary**



True progress!: *ab initio* nuclear $\Box_{\gamma W}$

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

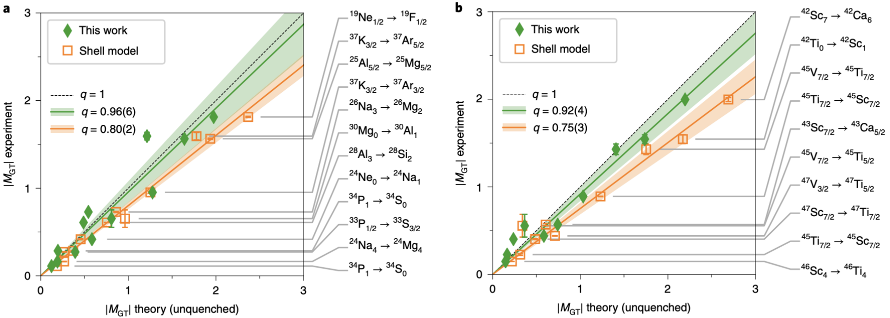
- IMSRG for closed and open-shell nuclei: IM-HF and IM-PHFB
  - HH, Phys. Scripta, Phys. Scripta 92, 023002 (2017)
  - HH, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tuskiyama, Phys. Rept. 621, 165 (2016)
- **Valence-Space IMSRG (VS-IMSRG)**
  - S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. 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, . . .

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

*P. Gysbers et al., Nature Physics **15**, 428 (2019)*



- **empirical Shell model** calculations require **quenching factors** of the weak axial-vector couling g_A
- **VS-IMSRG** explains this through consistent **renormalization** of transition operator, incl. **two-body currents**

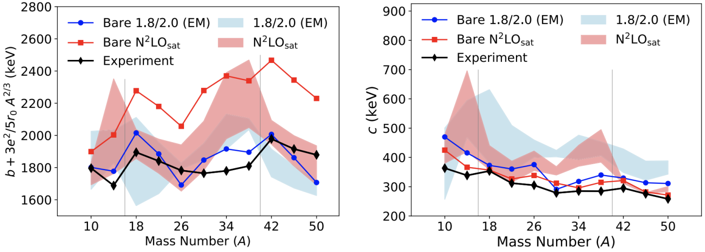
Going heavier: IM-SRG type methods (Slide by Jason Holt)

TRIUMF

Ab initio IMME: bare vs IMSRG

Isobaric mass multiplet equation (IMME) relates energies between members of multiplets

$$E(T_z) = a + bT_z + cT_z^2$$

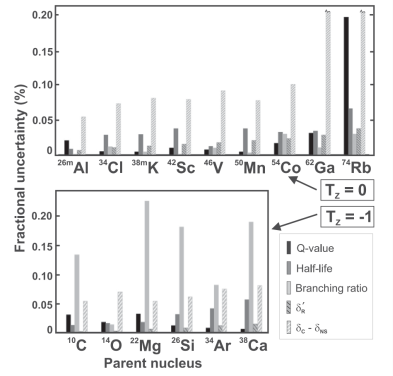


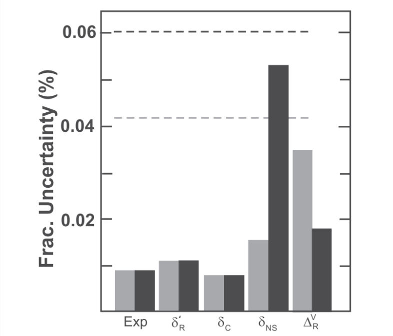
Bands: normal ordering reference dependence

Overall little effect/improvement when applying IMSRG transformation for both b, c

Superallowed summary

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





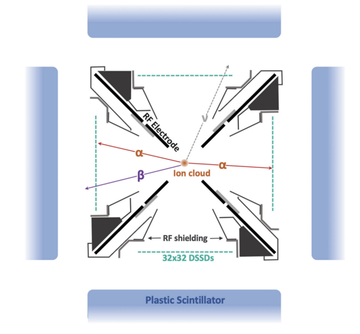
Moving towards mature *ab initio* theory evaluation

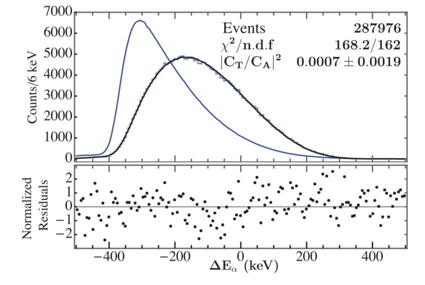
Hardy & Towner PRC 102 (2020) 045501

Highlight: Tensor constraints from 8Li

Improved Limit on Tensor Currents in the Weak Interaction from ^{8}Li β Decay

M. T. Burkey *et al.*
Phys. Rev. Lett. **128**, 202502 – Published 19 May 2022



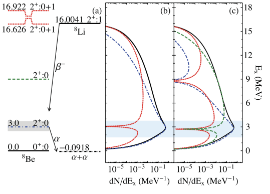


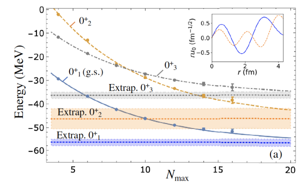
Highlight: Made possible by theory progress

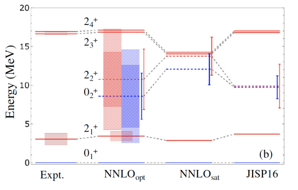
Impact of Clustering on the ^{8}Li β Decay and Recoil Form Factors

G. H. Sargsyan, K. D. Launey, M. T. Burkey, A. T. Gallant, N. D. Scielzo, G. Savard, A. Mercenne, T. Dytrych, D. Langr, L. Varriano, B. Longfellow, T. Y. Hirsh, and J. P. Draayer

Phys. Rev. Lett. **128**, 202503 – Published 19 May 2022



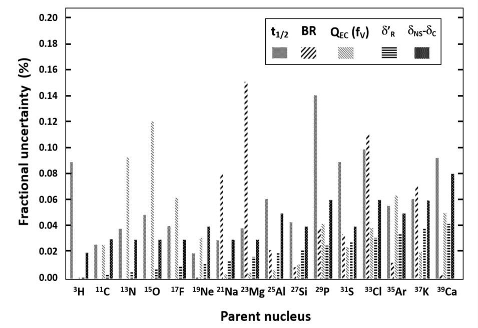


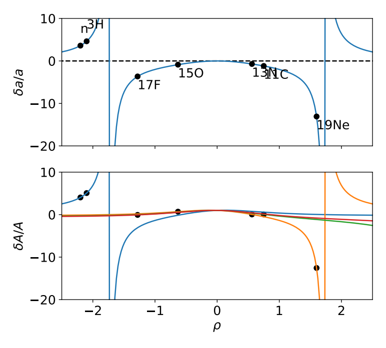


Clear need for new theory, ab initio delivered

Power of $T = 1/2$ mirror decays

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

^{6}He-CRES

SALER

with new spectroscopy techniques & traps

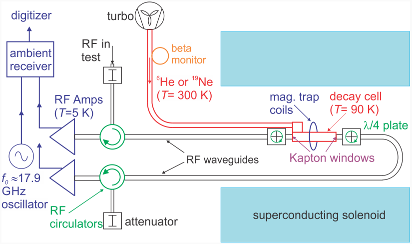
St. Benedict (Notre Dame) significant campaign to extend global data set

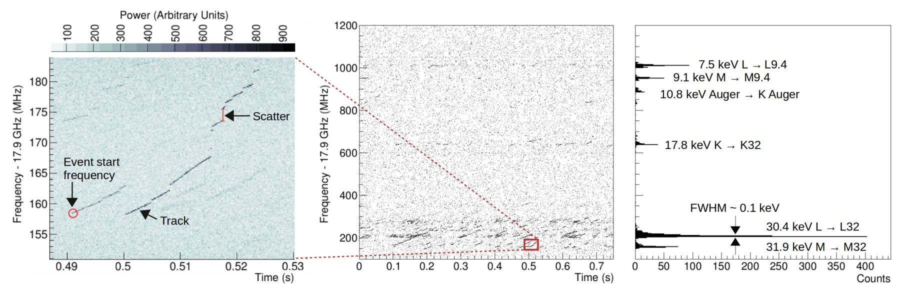
New technology: CRES

Cyclotron Radiation Emission Spectroscopy

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

^{6}He and ^{19}Ne



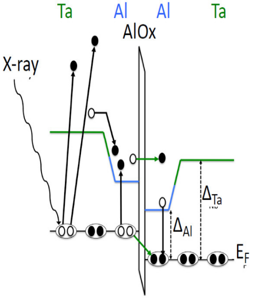


2209.02870

New technology: Superconducting Tunnel Junctions (Slide by Kyle

- 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*



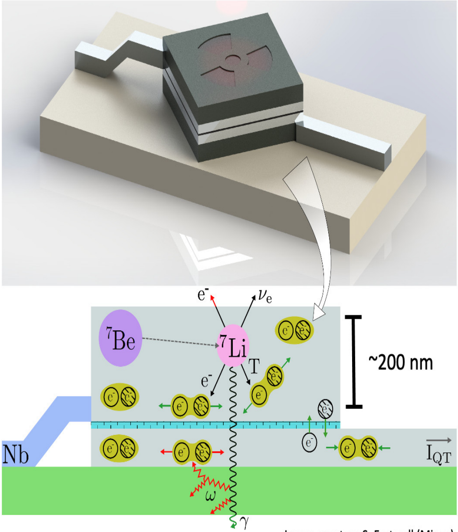
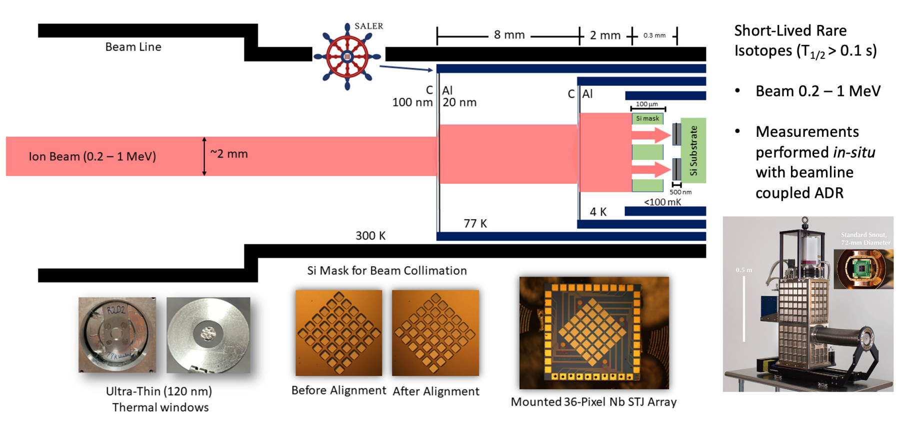


Image courtesy S. Fretwell (Mines)

SALER: Superconductiong Array for Low Energy Radiation

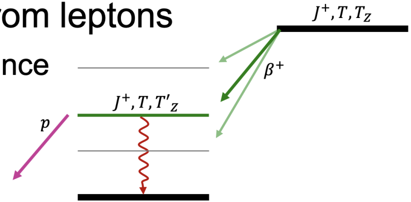
Measure recoiling nucleus instead, and at RIB

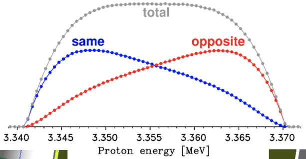


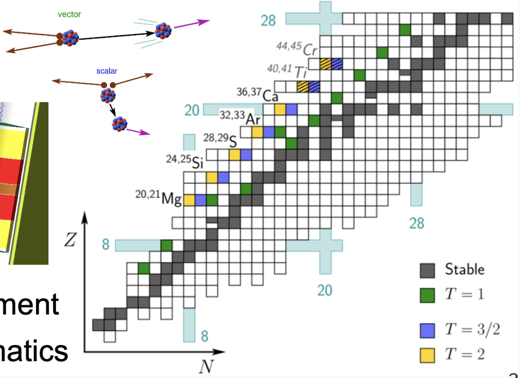
Portability allows easy installation (FRIB, SPIRAL2, ISOLDE, . . .)

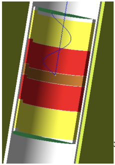
Angular correlations @ TAMUTRAP (Slide by Dan Melconian)

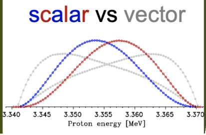
- Proton inherits information from leptons
  - β-ν correlation, Fierz interference sensitive to new physics (scalar/tensor currents)

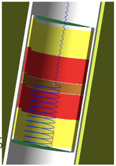






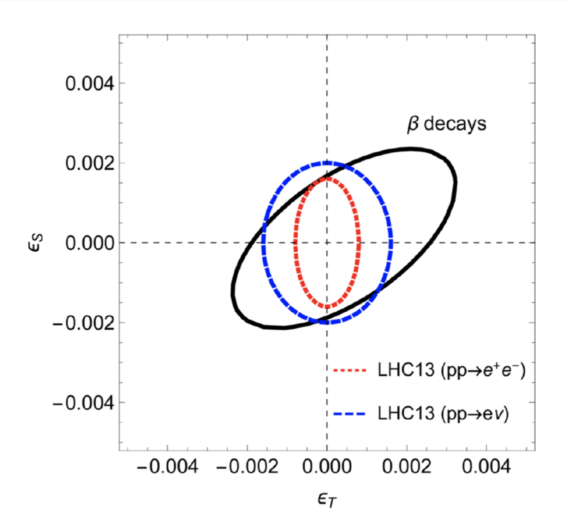






- *Extremely* clean measurement
- Many cases to test systematics

Exotic current status: complementary to LHC



Falkowski et al., JHEP 4 (2021) 126

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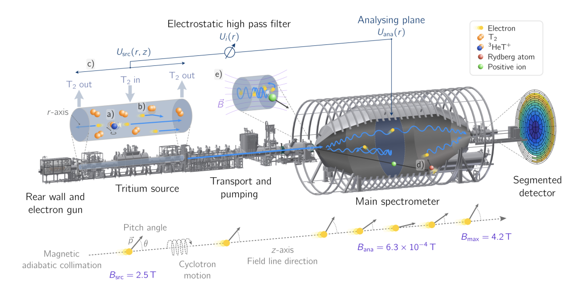
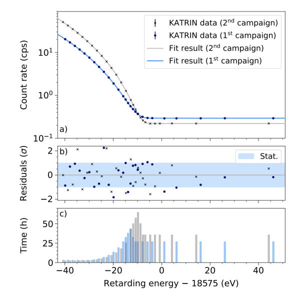
Neutrino mass measurements

Measuring ν mass in β/EC

Central idea: (admixture of exotic) neutrino shifts endpoint



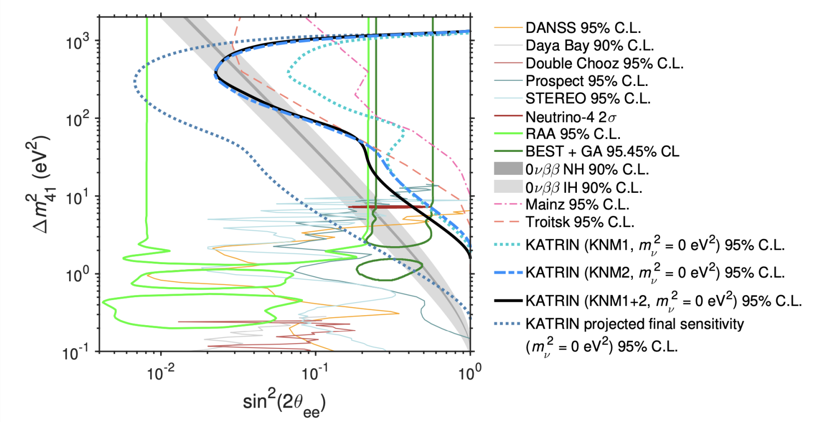


Final sensitivity $\sim 0.2\ \text{eV}/c^2$!

Also: Project 8, ECHo, Holmes, …

2105.08533

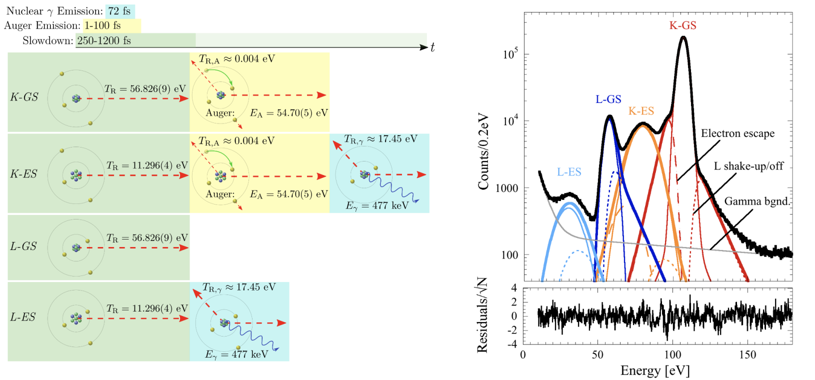
eV-scale sterile neutrino searches



2203.08059

Superconducting tunnel junctions (Slide by Kyle Leach)

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

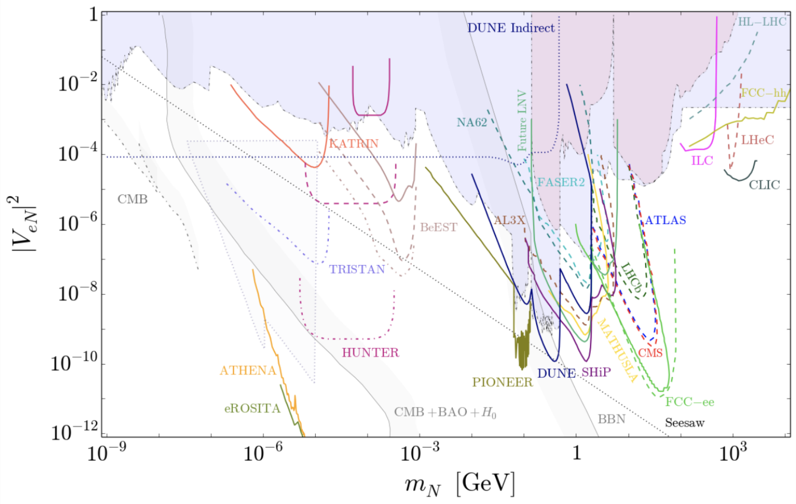


S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

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

Future sensitivities

β decay well-represented in eV→MeV searches



1912.03058, https://www.hep.ucl.ac.uk/∼pbolton/plots.html

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Looking forward

Symbiotic progress in precision experiments & ab initio theory to continue

Re-unlock $0^+ \rightarrow 0^+$ V_{ud} potential through collaborative theory effort for full mass range. Already, efforts underway $\rightarrow$ promising for next LRP

Innovative experimental techniques with very different systematics & discovery potential play to strengths of the field

Interesting future ahead!

Thank you!

Slides and conversations with Alejandro Garcia, Kyle Leach, Vincenzo Cirigliano, Emanuele Mereghetti, Dan Melconian, Saori Pastore, Andre Walker-Loud, Heiko Hergert, Ragnar Stroberg, Jason Holt, Jon Engel, Chien-Yeah Seng, Misha Gorchtein, Petr Navratil, Michael Gennari, . . .