Allowed and forbidden β-decays in ongoing BSM precision searches

Ayala Glick-Magid

UNIVERSITY of WASHINGTON

PAINT 2023

Allowed and forbid[redacted]ys
i[redacted]
[redacted]sion searches

Nuclear Uncertainty Matters!

Ayala Glick-Magid

UNIVERSITY of WASHINGTON

PAINT 2023

Also Matter!

Hebrew University
Doron Gazit
Guy Ron
Hitesh Rahangdale
Vishal Srivastava

TRIUMF
Petr Navrátil
Peter Gysbers
Lotta Jokiniemi

Chalmers University
Christian Forssén

ÚJF rez
Daniel Gazda

University of Barcelona
Javier Menéndez

NCSU
Leendert Hayen

LLNL
Nicholas Scielzo
Yonatan Mishnayot
Jason Harke
Aaron Gallant
Richard Hughes

SARAF (SOREQ)
Sergey Vaintraub
Tsviki Hirsh
Leonid Waisman
Arik Kreisel
Boaz Kaizer
Hodaya Dafna
Maayan Buzaglo

ETH Zurich
Ben Ohayon

Weizamnn Institute
Michael Hass

Ministry of Science and Technology, Israel
Israeli Science Foundation (ISF)
European Research Council (ERC)

Introduction: BSM exotic weak interactions

Theory — SM: uncertainties

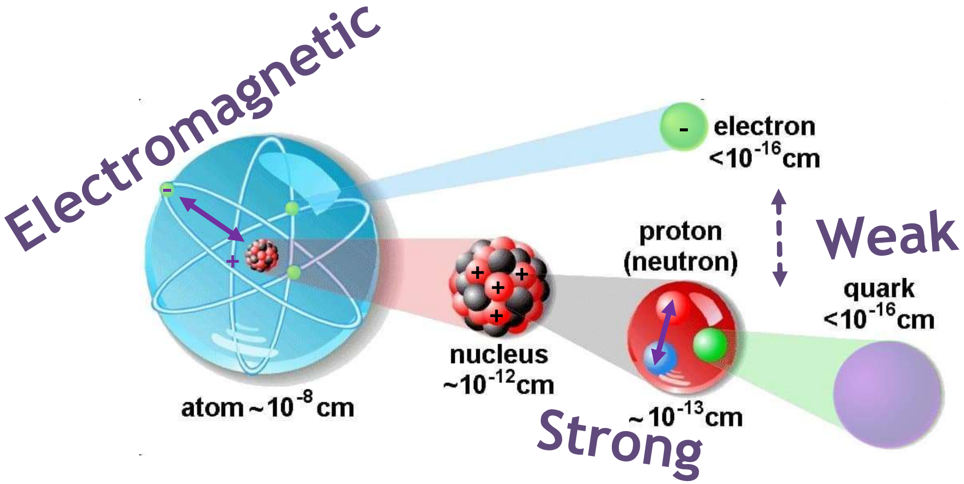
Expt. — Measurements: new bounds on BSM

Theory — BSM opportunities: new opportunities

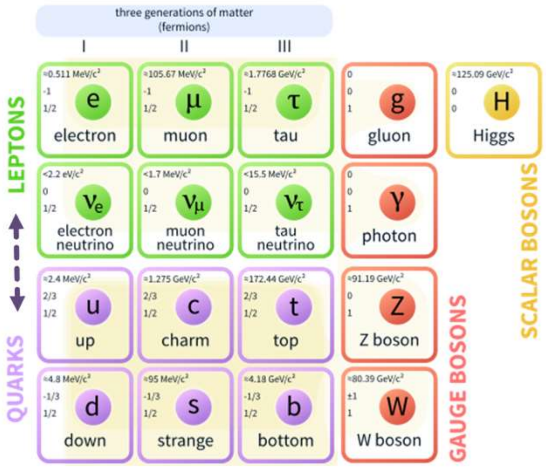
Summary: we can do it (and more)

Standard Model (SM)

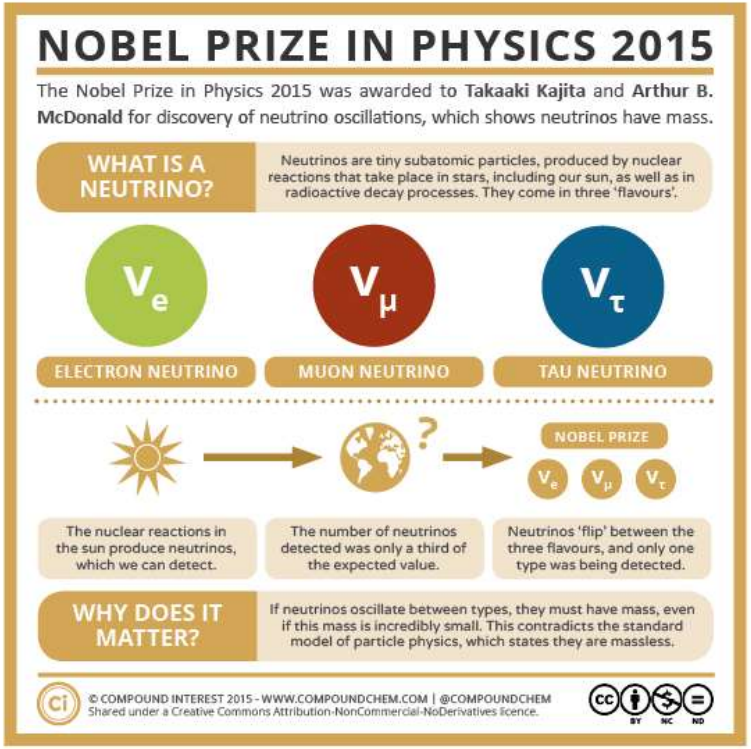
Fundamental Forces



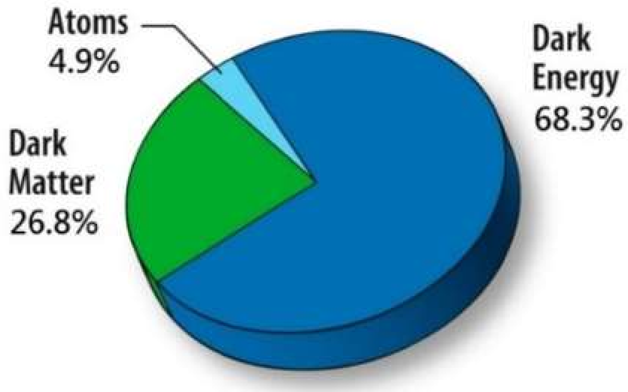
Elementary Particles



Beyond Standard Model (BSM)



The **Neutrino** has mass, even though according to the SM it should not (interacts only through the **Weak** interaction)



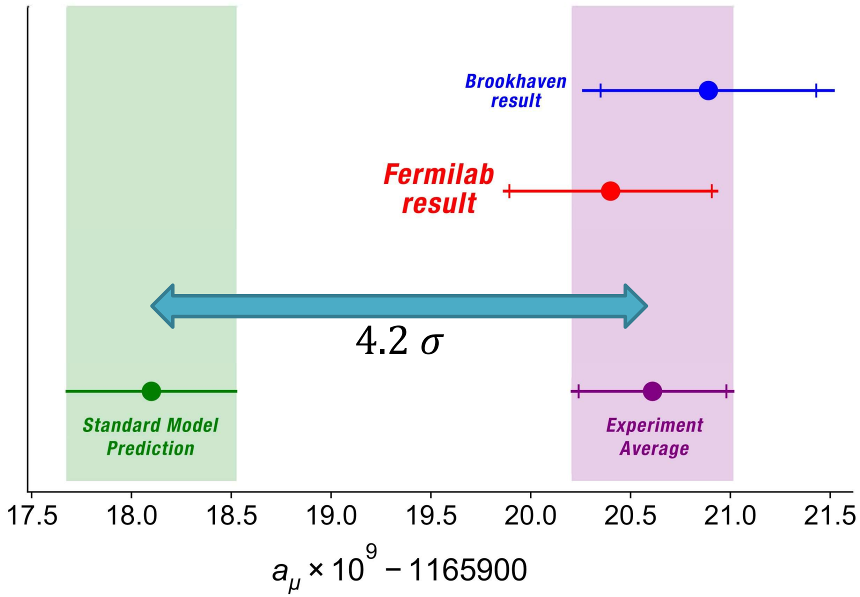
Dark Matter & Energy

Beyond Standard Model (BSM)

Deviations from the SM at high precision:

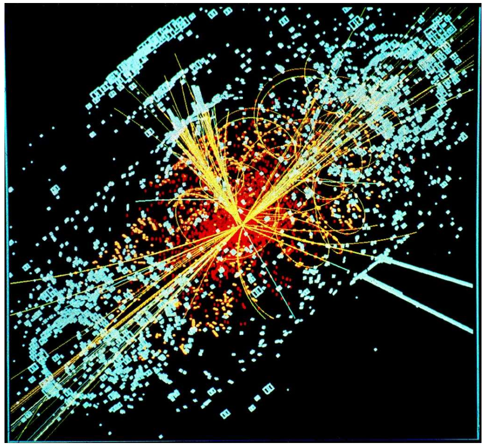
First results from Fermilab's Muon g-2 experiment strengthen evidence of new physics

April 7, 2021



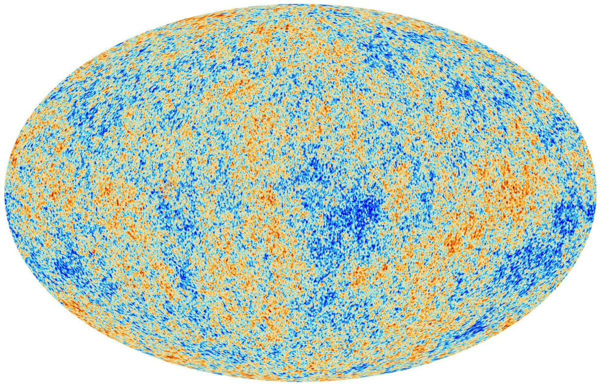
Searches for BSM physics

High energy frontier



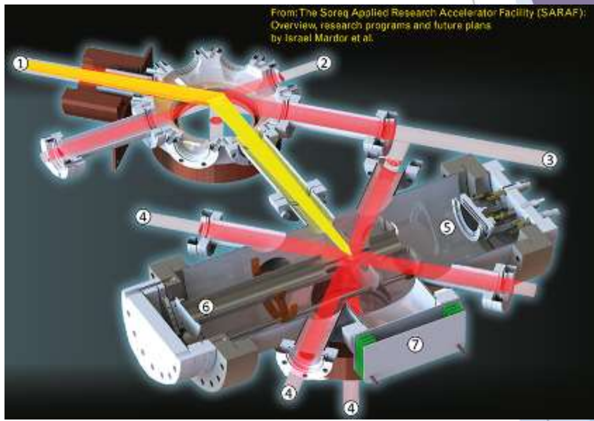
Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469

Astronomical frontier



https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

Precision frontier



Mardor *et al.*, Eur.Phys.J.A 54, 91 (2018)

LHC
TeV scale ⟷ Nuclear phenomena
10^{-3} precision level

new experiments

Nuclear structure challenge?

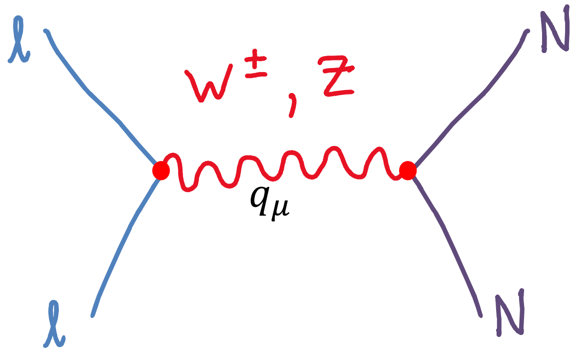
Doron: Nuclear theory can do that

Weak interaction

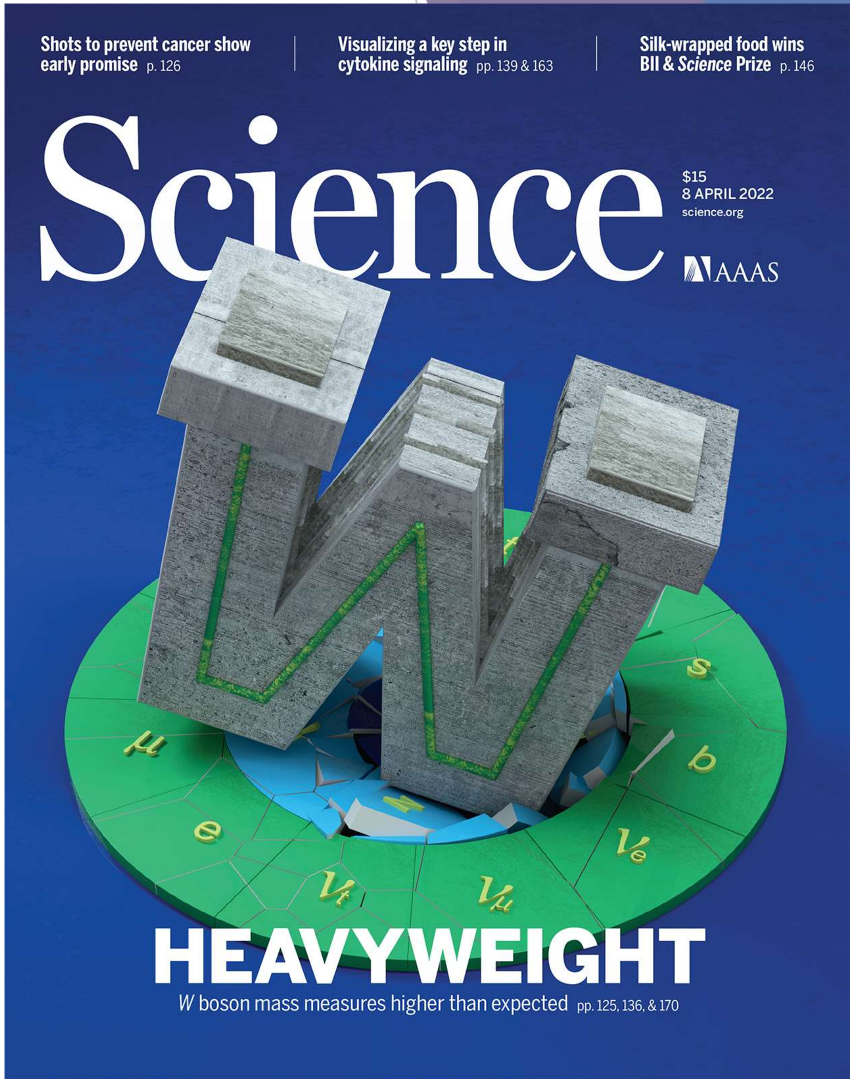
Low energy reaction of
leptons with nucleons

W Propagator:

$$\frac{g_{\mu\nu} + \frac{q_\mu q_\nu}{M_W^2}}{q^2 + M_W^2} \rightarrow \frac{g_{\mu\nu}}{M_W^2}$$



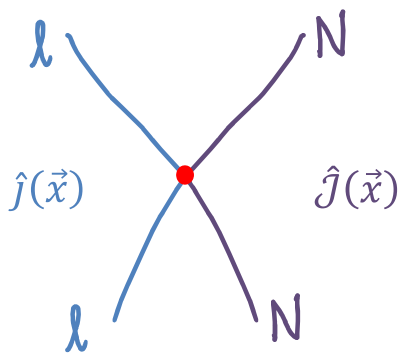
$$q \ll M_W$$



Weak interaction

Low energy reaction of
leptons with nucleons

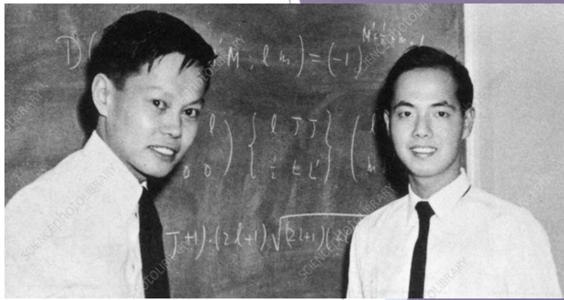
lepton
current



nuclear
current

$$\hat{\mathcal{H}}_W \sim C\, \hat{j}(\vec{x}) \cdot \hat{J}(\vec{x})$$

A-priori:
- Scalar (C_S)
- PseudoScalar (C_P)
- Vector (C_V)
- Axial vector (C_A)
- Tensor (C_T)



Theory: C.N. Yang and T.D. Lee (Nobel 1957)

Experiment: C.S. Wu:
Parity violation in ***nuclear β-decays***

$\Rightarrow$ **Weak SM structure: "$V - A$"**

The SM is incomplete

>> Ongoing searches for C_S, C_P, C_T
in precision ***nuclear β-decay*** experiments

Nuclear β-decay

Low momentum transfer: $q \sim 0 - 10\ \mathrm{MeV/c}$

angular momentum

parity

Transitions $J^{\Delta\pi}$:

"Allowed" (when $q \to 0$)	• 0^+: Fermi • 1^+: Gamow-Teller
"Forbidden" (vanish for $q \to 0$)	• All the rest $J^{\Delta\pi}$ • Missing theory for BSM tensor

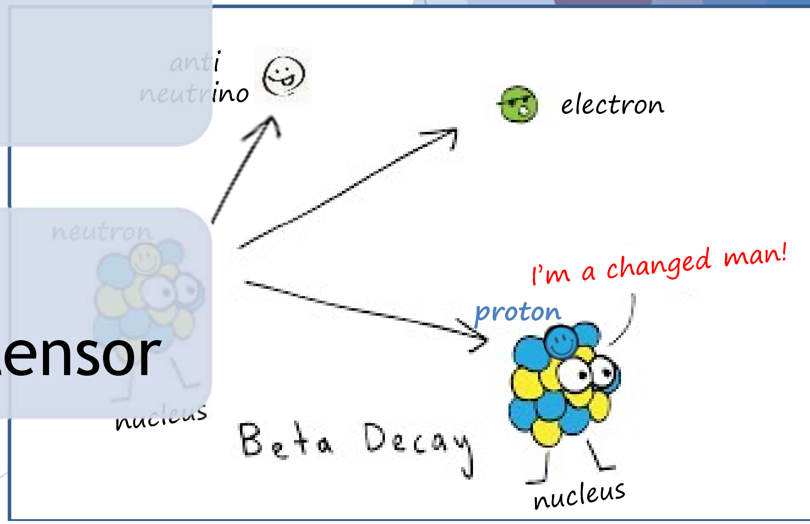


Fig.: Beta decay, Khan Academy, cdn.kastatic.org/ka-perseus-images/3d978444f15f9bbc3bcadb0549816bc7e264b977.svg

Nuclear β-decay

- β-decay rate:

$$d\omega \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \underset{allowed}{\propto} 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\text{F}}\frac{m_e}{E}$$

electron's mass, energy

Observables

Measurements ***(e.g., Gamow-Teller):***

Assuming a TeV scale

- **Angular correlation:** $a_{\beta\nu} = \underbrace{-\frac{1}{3}}_{\text{SM}}\left(1 - \overbrace{\frac{|C_T^+|^2 + |C_T^-|^2}{4|C_A|^2}}^{\text{BSM}}\right) \sim 10^{-6}$
  - Quadratic in C_T^+, C_T^-
- **Energy spectrum**: Fierz term $b_{\text{F}}^{\beta^\mp} = \underbrace{0}_{\text{SM}} \pm \overbrace{\frac{C_T^+}{C_A}}^{\text{BSM}} \sim 10^{-3}$
  - Vanishes for right-handed neutrinos ($C_T^+ = 0$)

new experiments aim $\lesssim 10^{-3}$ precision level

$C_A = 1.27$ Axial vector coupling constant (SM)

$\underbrace{C_T^+(C_T^-)}_{\epsilon_T} \lesssim 10^{-3}$ Tensor left (right) coupling constants (BSM), unknown

Nuclear β-decay

- β-decay rate:

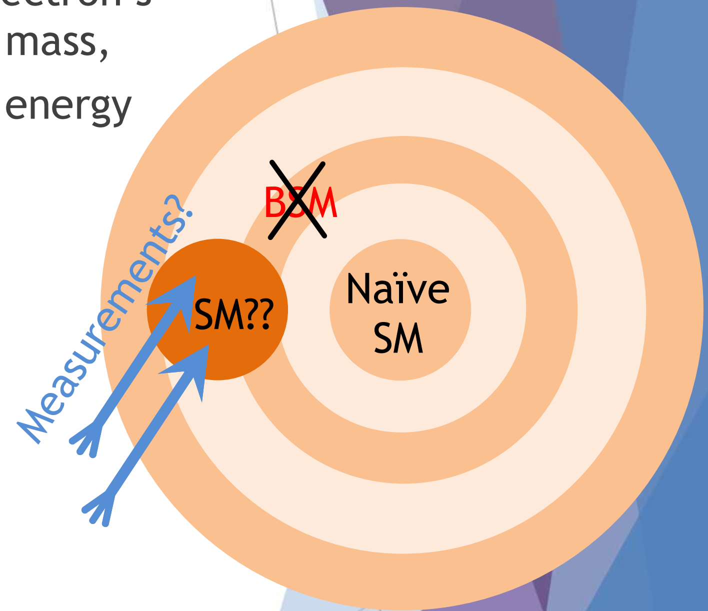
$$d\omega \propto \left|\langle\psi_f\|\widehat{H}_W\|\psi_i\rangle\right|^2 \underset{\substack{allowed\\ q\to 0}}{\propto} 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{E}$$

electron's mass, energy

Observables

Measurements ***(e.g., Gamow-Teller):***

- **Angular correlation:** $a_{\beta\nu} = \underbrace{-\frac{1}{3}}_{\text{SM}}\left(1 - \underbrace{\frac{|C_T^+|^2+|C_T^-|^2}{4|C_A|^2}}_{\text{BSM}}\right)$
  - Quadratic in C_T^+, C_T^-
- **Energy spectrum:** Fierz term $b_{\mathrm{F}}^{\beta^\mp} = \underbrace{0}_{\text{SM}} \pm \underbrace{\frac{C_T^+}{C_A}}_{\text{BSM}}$
  - Vanishes for right-handed neutrinos ($C_T^+ = 0$)



Searches for deviations from the SM "V-A" structure

>> More accurate theory is needed

Standard Model
high order corrections

Identifying small parameters

q - momentum transfer
R - nucleus's radius
m_N - nucleon's mass
P_{fermi} - Fermi momentum
α - fine structure constant
Z - final nucleus's charge

- Kinematic parameters – β-decays have low momentum transfer:
  - $\epsilon_{qr} \sim qR \approx 0.01A^{1/3}$ *
  - $\epsilon_{\text{recoil}} \sim \frac{q}{m_N} \approx 0.002$ *
- The Coulomb force:
  - $\epsilon_c \sim \alpha Z \approx 0.007Z$
- **The nuclear model:**
  - $\epsilon_{\text{NR}} \sim \frac{P_{\text{fermi}}}{m_N} \approx 0.2$
  - $\boldsymbol{\epsilon_{\text{EFT}}} \sim \mathbf{0.1}$
- **Numeric calculation:**
  - $\boldsymbol{\epsilon_{\text{solver}}}$

* For an endpoint of $\sim 2\ MeV$

AGM & Gazit, J.Phys.G **49** 105105 (2022)

SM corrections

- β-decay rate:

e.g., Gamow-Teller

$$d\omega \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \quad \propto \quad 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{E}$$

Angular correlation

$a_{\beta\nu}$: $\underbrace{-\frac{1}{3}}_{\text{SM}}\underbrace{(1+\delta_a)}_{\text{SM correction}}$

Fierz term

b_{F}: $\underbrace{0}_{\text{SM}} + \underbrace{\delta_b}_{\text{SM correction}}$

Multipole operator's matrix elements between the nuclear states

- $$\delta_b = f_b\underbrace{\left(\frac{\langle\psi_f\|\hat{C}_{\mathrm{J}}^{A}\|\psi_i\rangle}{\langle\psi_f\|\hat{L}_{\mathrm{J}}^{A}\|\psi_i\rangle}, \frac{\langle\psi_f\|\hat{M}_{\mathrm{J}}^{V}\|\psi_i\rangle}{\langle\psi_f\|\hat{L}_{\mathrm{J}}^{A}\|\psi_i\rangle}\right)}_{\sim\,\epsilon_{\mathrm{NR}}\epsilon_{qr},\,\epsilon_{\mathrm{recoil}}\ \sim 10^{-2}} + \mathcal{O}\underbrace{\left(\frac{\epsilon_{qr}^2}{15}, \epsilon_c^2\right)}_{\sim 5\cdot 10^{-4}}$$

AGM & Gazit, J.Phys.G **49** 105105 (2022)

$$\epsilon_{\mathrm{NR}} \sim \frac{p_{\mathrm{fermi}}}{m_N} \approx 2\cdot 10^{-1}$$
$$\epsilon_{\mathrm{EFT}} \sim 1\cdot 10^{-1}$$
$$\epsilon_{qr} \sim qR \approx 5\cdot 10^{-2}$$
$$\epsilon_c \sim \alpha Z_f \approx 2\cdot 10^{-2}$$
$$\epsilon_{\mathrm{recoil}} \sim \frac{q}{m_N} \approx 4\cdot 10^{-3}$$

Multipole Expansion

General Theory - for any nucleus & transition

Measurements

Experimental status over the world

Energy spectrum - b_F

TABLE III. List of nuclear β-decay spectral measurements in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
β spectrum	GT	^{114}In	MiniBETA-Krakow-Leuven	0.1 %
β spectrum	GT	^{6}He	LPC-Caen	0.1 %
β spectrum	GT	^{6}He, ^{20}F	NSCL-MSU	0.1 %
β spectrum	GT, F, Mixed	^{6}He, ^{14}O, ^{19}Ne	He6-CRES	0.1 %

Angular correlation - $a_{\beta\nu}$

TABLE I. List of nuclear β-decay correlation experiments in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
$\beta - \nu$	F	^{32}Ar	Isolde-CERN	0.1 %
$\beta - \nu$	F	^{38}K	TRINAT-TRIUMF	0.1 %
$\beta - \nu$	GT, Mixed	^{6}He, ^{23}Ne	SARAF	0.1 %
$\beta - \nu$	GT	^{8}B, ^{8}Li	ANL	0.1 %
$\beta - \nu$	F	^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ...	TAMUTRAP-Texas A&M	0.1 %
$\beta - \nu$	Mixed	^{11}C, ^{13}N, ^{15}O, ^{17}F	Notre Dame	0.5 %
β & recoil asymmetry	Mixed	^{37}K	TRINAT-TRIUMF	0.1 %

Cirigliano *et al.*, arXiv:1907.02164v2 (2019)

Ab initio calculations of $^{6}\mathrm{He} \xrightarrow{\beta^-} {}^{6}\mathrm{Li}$

$\hat{H}$

Nuclear Hamiltonian

χEFT @ $\mathrm{N^2LO_{opt\,(sat)}}$

$\hat{J}(\vec{x})$

Nuclear currents

LO (1-body currents)

$\langle \psi_f \| \quad \| \psi_i \rangle$

Nuclear wave functions

$\hat{O}_J$

Multipole operators

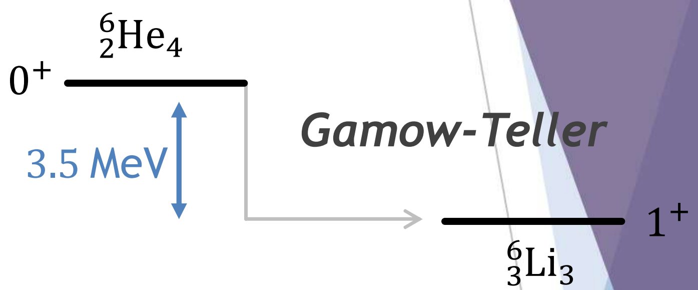
$\langle \psi_f \| \hat{O}_J \| \psi_i \rangle$

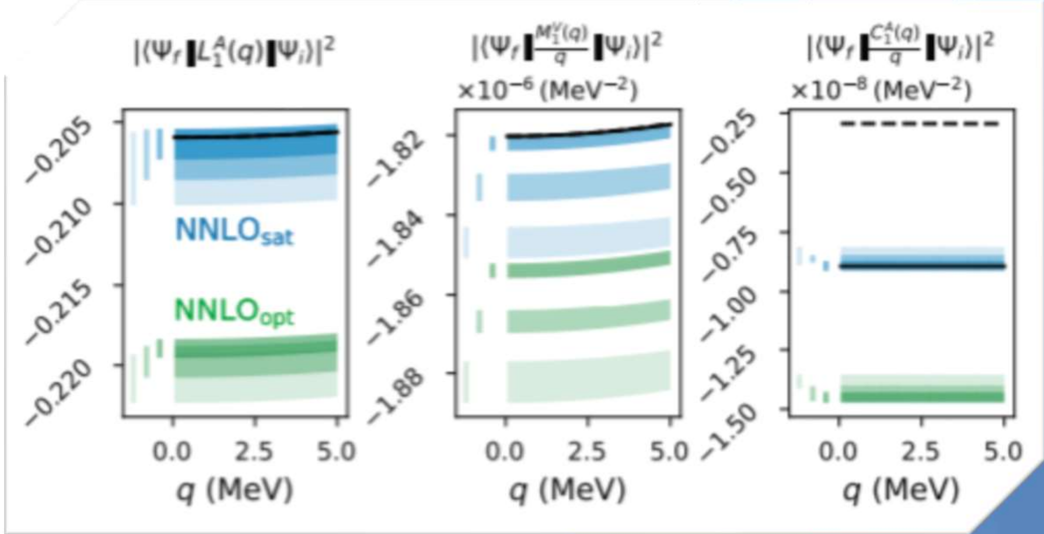
Nuclear matrix elements

Ab initio No-Core Shell Model (NCSM)

δ_a, δ_b

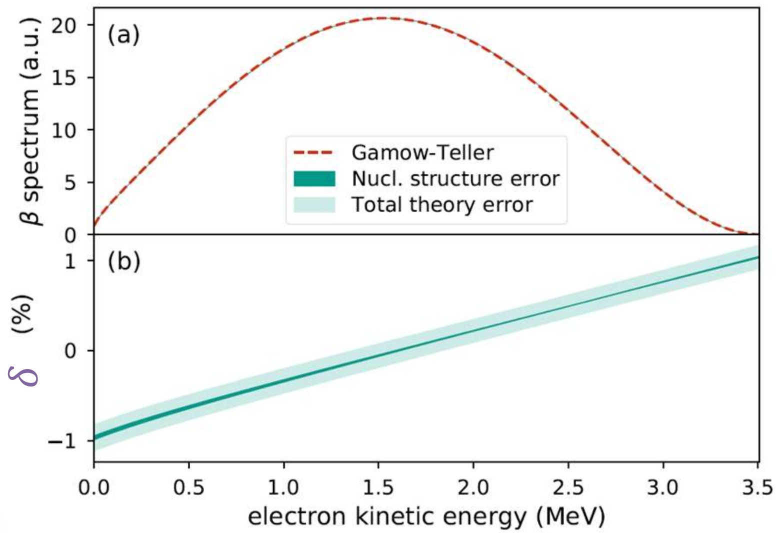
Observables' corrections





AGM, **Forssén**, Gazda, **Gazit**, **Gysbers** & **Navrátil**, Phys.Lett.B **832** 137259 (2022)

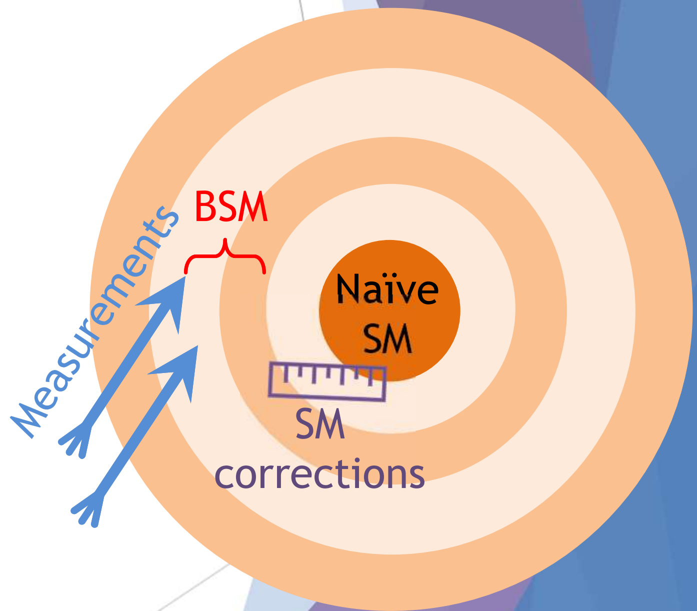
$^6\mathrm{He} \to {}^6\mathrm{Li}$ β-energy spectrum



- Experiments are aiming a 10^{-3} accuracy
- The spectrum is used to find Fierz term:

$$b_F = \underbrace{0}_{\text{SM}} + \underbrace{\delta_b}_{\text{SM correction}} + \underbrace{\frac{C_T^+}{C_A}}_{\text{BSM}}$$

- Looking for $\frac{C_T^+}{C_A} \sim 10^{-3}$
- $\delta_b = -1.52(18) \cdot 10^{-3}$
- Uncertainty $< 2 \cdot 10^{-4}$



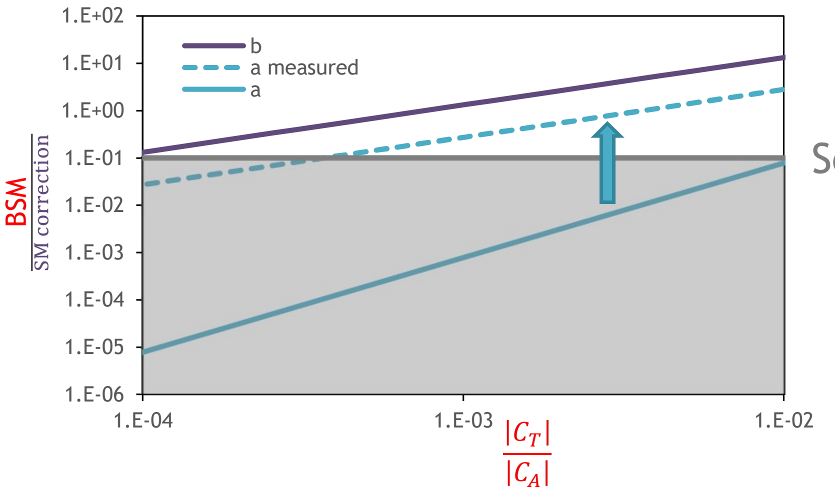
AGM, **Forssén**, Gazda, **Gazit**, **Gysbers** & **Navrátil**, [Phys.Lett.B **832** 137259] (2022)

$^6\mathrm{He} \rightarrow\ ^6\mathrm{Li}$ angular correlation

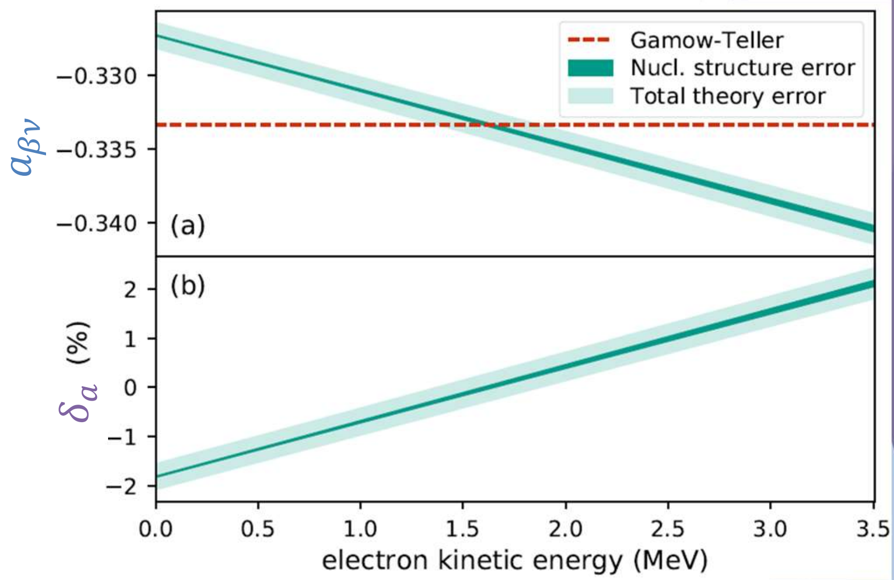
- Experiments are aiming a 10^{-3} accuracy

- $$a_{\beta\nu} = -\frac{1}{3}\Big(\underbrace{1}_{\text{GT}} + \underbrace{\tilde{\delta}_a}_{\text{SM correction}} + \underbrace{\frac{|C_T^+|^2+|C_T^-|^2}{4|C_A|^2}}_{\text{BSM}}\Big)$$

- Looking for $\frac{|C_T^+|^2+|C_T^-|^2}{4|C_A|^2} \sim \mathbf{10^{-6}}$ **???**



Sensitivity



$\tilde{\delta}_a = -2.54(68) \cdot 10^{-3}$

$C_T^+(C_T^-) \sim 10^{-3}$

$$\boxed{a_{\beta\nu}^{\text{measured}} \propto \cdots - \mathbf{0.1}\, b_F \sim \mathbf{0.1}\frac{C_T^+}{C_A} \sim \mathbf{10^{-4}}\ \textbf{!!!}}$$

Future experiments aim at < 10^{-3}

AGM, **Forssén**, Gazda, **Gazit**, **Gysbers** & **Navrátil**, Phys.Lett.B **832** 137259 (2022)

PHYSICAL REVIEW LETTERS **129,** 182502 (2022)

β-Nuclear-Recoil Correlation from ^{6}He Decay in a Laser Trap

P. Müller,[1] Y. Bagdasarova,[2] R. Hong,[2] A. Leredde,[1] K. G. Bailey,[1] X. Fléchard,[3] A. García,[2] B. Graner,[2] A. Knecht,[2,4] O. Naviliat-Cuncic,[3,5] T. P. O'Connor,[1] M. G. Sternberg,[2] D. W. Storm,[2] H. E. Swanson,[2] F. Wauters,[2,6] and D. W. Zumwalt[2]

$$\hat{a} = -0.3268(46)_{\mathrm{stat}}(41)_{\mathrm{syst}}. \tag{4}$$

Assuming tensor contributions with right-handed neutrinos ($b = 0$ or $\tilde{C}_T = -\tilde{C}'_T$) the result above implies $|\tilde{C}_T|^2 \leq 0.022$ (90% C.L.) On the other hand, assuming purely left-handed neutrinos ($\tilde{C}_T = +\tilde{C}'_T$) yields

$$0.007 < \tilde{C}_T < 0.111 \text{ (90\% C.L.)}. \tag{5}$$

Experimental status over the world

Energy spectrum - b_F

TABLE III. List of nuclear β-decay spectral measurements in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
β spectrum	GT	^{114}In	MiniBETA-Krakow-Leuven	0.1 %
β spectrum	GT	^{6}He	LPC-Caen	0.1 %
β spectrum	GT	^{6}He, ^{20}F	NSCL-MSU	0.1 %
β spectrum	GT, F, Mixed	^{6}He, ^{14}O, ^{19}Ne	He6-CRES	0.1 %

Angular correlation - $a_{\beta\nu}$

TABLE I. List of nuclear β-decay correlation experiments in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
$\beta-\nu$	F	^{32}Ar	Isolde-CERN	0.1 %
$\beta-\nu$	F	^{38}K	TRINAT-TRIUMF	0.1 %
$\beta-\nu$	GT, Mixed	^{6}He, ^{23}Ne	SARAF	0.1 %
$\beta-\nu$	GT	^{8}B, ^{8}Li	ANL	0.1 %
$\beta-\nu$	F	^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ...	TAMUTRAP-Texas A&M	0.1 %
$\beta-\nu$	Mixed	^{11}C, ^{13}N, ^{15}O, ^{17}F	Notre Dame	0.5 %
β & recoil asymmetry	Mixed	^{37}K	TRINAT-TRIUMF	0.1 %

SOREQ Soreq Nuclear Research Center

Cirigliano *et al.*, arXiv:1907.02164v2 (2019)

$^{23}\mathrm{Ne} \rightarrow {}^{23}\mathrm{Na}$

$\hat{H}$

Nuclear Hamiltonian
USDB (USD)

$\hat{\mathcal{J}}(\vec{x})$

Nuclear currents
LO (1-body currents)

$\langle \psi_f \| \quad \| \psi_i \rangle$

Nuclear wave functions

$\hat{O}_J$

Multipole operators

$\langle \psi_f \| \hat{O}_J \| \psi_i \rangle$

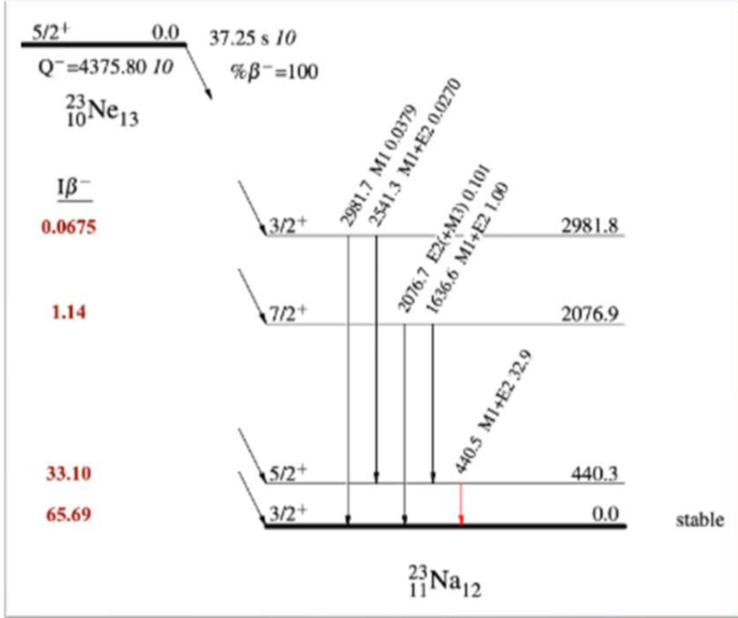
Nuclear matrix elements
Shell Model $\sim \mathbf{10^{-1}}$ **uncertainty**

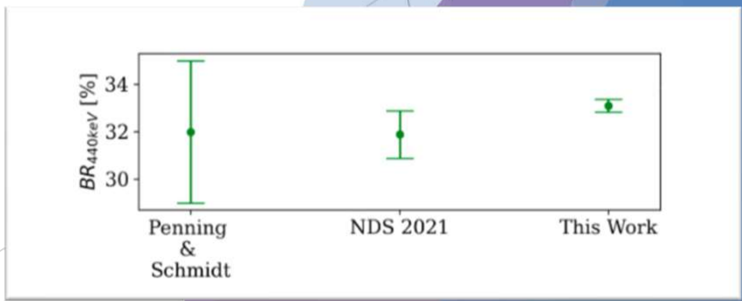
δ_a, δ_b

Observables' corrections

. . .

SARAF: measuring $^{23}\mathrm{Ne}$'s branching ratio with a $\sim \mathbf{5 \cdot 10^{-3}}$ **uncertainty**

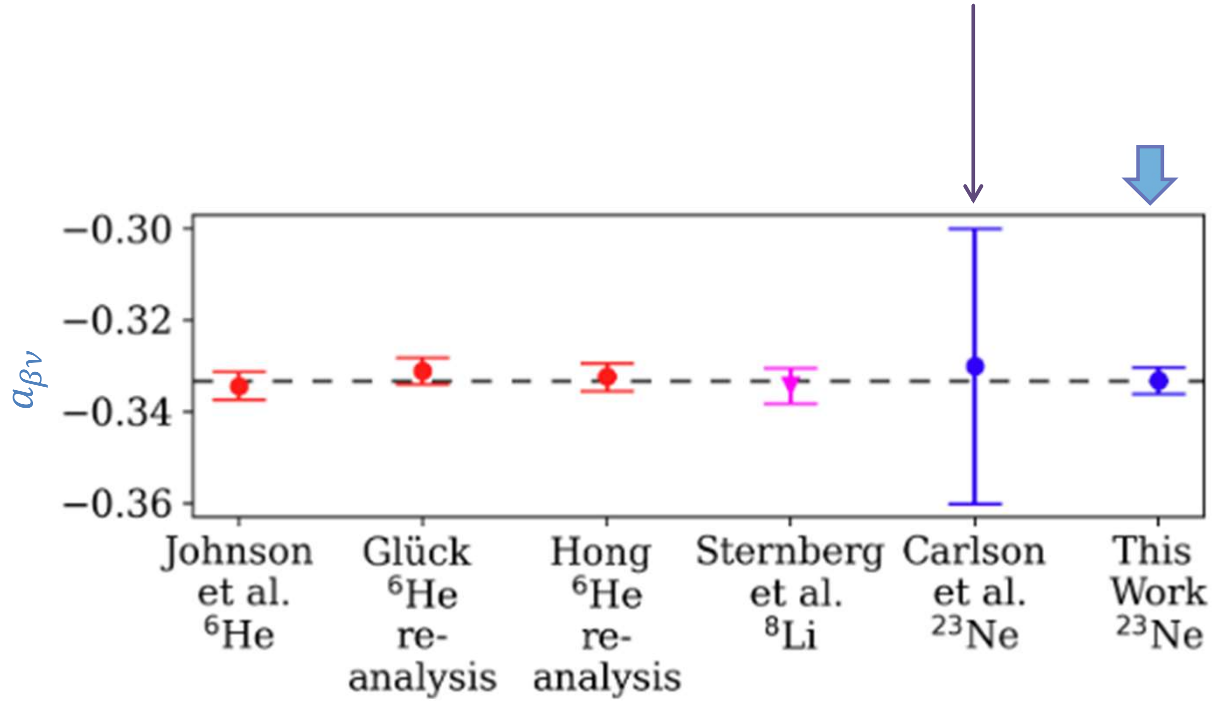




Mishnayot, AGM, **Forssén**, Gazda, **Gazit**, **Gysbers**, Menéndez & **Navrátil**, *et al.*, arXiv:2107.14355

$^{23}\mathrm{Ne} \rightarrow {}^{23}\mathrm{Na}$

Reanalyzing measurements of Carlson *et al.*, PhysRev132.2239 (1963)

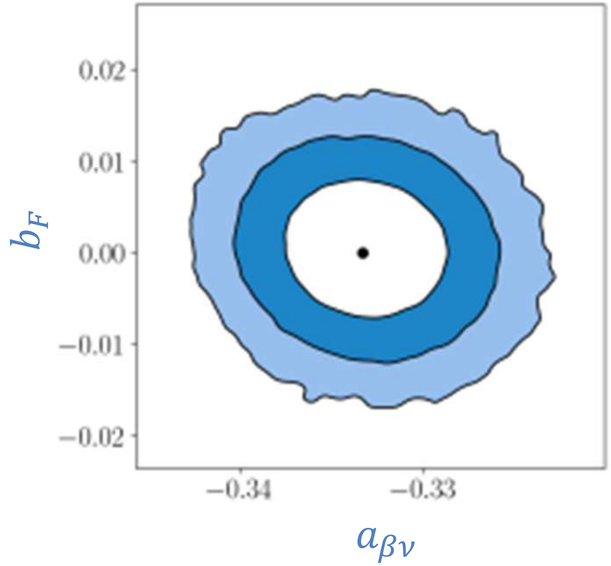


Mishnayot, AGM, **Forssén**, Gazda, **Gazit**, **Gysbers**, Menéndez & **Navrátil**, *et al.*, arXiv:2107.14355

$^{23}\mathrm{Ne} \to {}^{23}\mathrm{Na}$

Reanalyzing measurements of Carlson *et al.*, PhysRev132.2239 (1963)

Constraining $a_{\beta\nu}$ & b_F simultaneously



statistics experiment theory

$$a_{\beta\nu} = -0.3331 \pm 0.0028 \pm 0.0004 \pm 0.0002$$
$$b_F = 0.0007 \pm 0.0049 \pm 0.0003 \pm 0.0001$$

Mishnayot, AGM, **Forssén**, Gazda, **Gazit**, **Gysbers**, Menéndez & **Navrátil**, *et al.*, arXiv:2107.14355

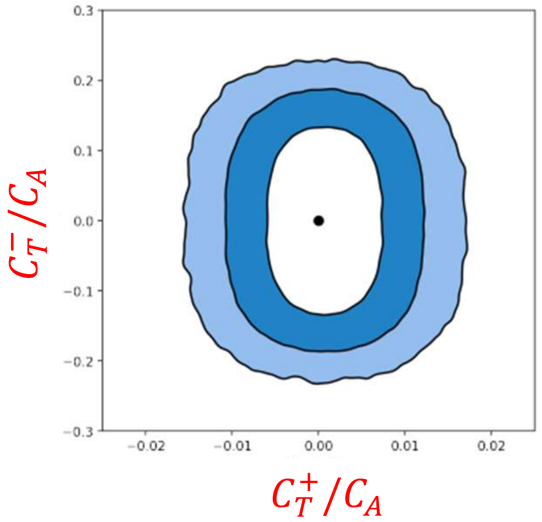
$^{23}\mathrm{Ne} \to {}^{23}\mathrm{Na}$

Not final

$^{23}\mathrm{Ne} \rightarrow {}^{23}\mathrm{Na}$

Reanalyzing measurements of Carlson *et al.*, PhysRev132.2239 (1963)

New constraints on the existence of exotic Tensor interactions



$$\frac{C_T^+}{C_A} = 0.0007 \pm 0.0049 \qquad \frac{C_T^-}{C_A} = 0.0001 \pm 0.0823$$

Not final

Mishnayot, AGM, **Forssén**, Gazda, **Gazit**, **Gysbers**, Menéndez & **Navrátil**, *et al.*, arXiv:2107.14355

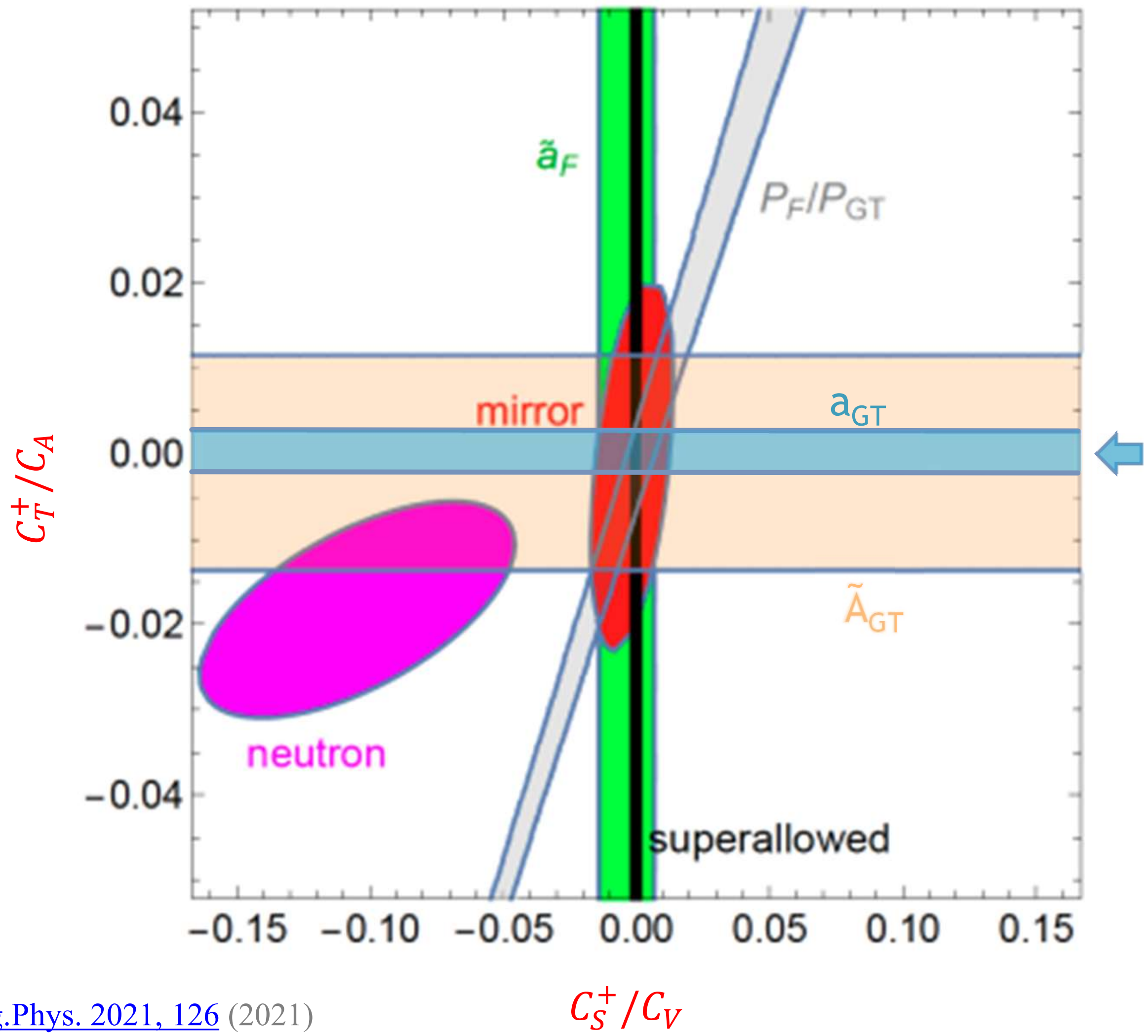


Fig: Falkowski *et al*., [J.High Energ.Phys. 2021, 126](#) (2021)

Not final

New opportunity: BSM missing theory

SM multipole expansion

- β-decay rate:

$$d\omega \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \quad \propto \quad \sum_{J=0}^{\infty} f^A\left(\vec{\beta},\hat{\nu}\right)\langle\psi_f\|\hat{O}_J^A\|\psi_i\rangle\langle\psi_f\|\hat{Q}_J^A\|\psi_i\rangle^*$$

Observables

Multipole operators

$$\hat{\mathcal{H}}_W \sim C_A\, \hat{j}^\mu(\vec{x})\hat{\mathcal{J}}_\mu(\vec{x})$$

Axial coupling constant

Axial Lepton current

Axial nuclear current

4 multipole operators: $\hat{C}_J^A,\ \hat{L}_J^A,\ \hat{E}_J^A,\ \hat{M}_J^A$

e.g., $\hat{M}_{JM}^A = \int d^3x\left[j_J(qx)\,\vec{Y}_{JJ1}^M(\hat{x})\right]\cdot\vec{\mathcal{J}}(\vec{x})$

Axial nuclear current

and the same for the Vector (V) symmetry

BSM multipole expansion

- β-decay rate:

$$d\omega \propto \left|\langle \psi_f \| \hat{H}_W \| \psi_i \rangle\right|^2 \quad \propto \sum_{J=0}^{\infty} f^T\left(\vec{\beta}, \hat{\nu}\right) \langle \psi_f \| \hat{O}_J^T \| \psi_i \rangle \langle \psi_f \| \hat{Q}_J^T \| \psi_i \rangle^*$$

Observables

Multipole operators

$$\hat{\mathcal{H}}_W \sim C_T\, \hat{j}^{\mu\nu}(\vec{x}) \hat{\mathcal{J}}_{\mu\nu}(\vec{x})$$

Tensor coupling constant

Tensor Lepton current

Tensor nuclear current

4 multipole operators: $\hat{C}_J^T, \hat{L}_J^T, \hat{E}_J^T, \hat{M}_J^T$

e.g., $\hat{M}_{JM}^T = \int d^3x \left[j_J(qx)\, \cancel{\vec{Y}_{JJ1}^M(\hat{x})} \right] \cdot \hat{\mathcal{J}}_{\mu\nu}(\vec{x})$

Tensor nuclear current

The currents are tensors: $\hat{j}^{\mu\nu}(\vec{x}) \hat{\mathcal{J}}_{\mu\nu}(\vec{x})$

AGM & Gazit, arXiv:2207.01357, in press. Phys. Rev. D (2023)

Tensor $\longrightarrow$ vector-like objects

$$\hat{\mathcal{H}}_W \sim C_{\mathrm{T}}\, \hat{j}^{\mu\nu}(\vec{x})\, \hat{J}^{T}_{\mu\nu}(\vec{x})$$

Lepton current

Nuclear current

Tensor interactions

- ~~Symmetric:~~
  - ~~A space-time-metric and the stress-energy tensor~~
- Antisymmetric
  - Fermionic probes

$$\Longrightarrow l_{00} = 0$$

$$\Longrightarrow l_{\cdot 0} = -l_{0\cdot}$$

$$\Longrightarrow l_{ij} \longrightarrow \left[l_{ij}\right]^{(1)}$$

$$l_{\mu\nu} = \begin{pmatrix} \cancel{l_{00}} & \left(\leftarrow \; \vec{l}_{0\cdot} \; \rightarrow \right) \\ \begin{pmatrix} \uparrow \\ -\vec{l}_{0\cdot} \\ \downarrow \end{pmatrix} & \begin{pmatrix} \vec{l}^{(1)} \end{pmatrix} \end{pmatrix}$$

AGM & Gazit, arXiv:2207.01357, in press. Phys. Rev. D (2023)

Tensor $\rightarrow$ vector-like objects

- Tensor “vector-like” multipole operators with an identified parity

and the same **exact** relations for the other tensor operators ($\hat{E}_J^T, \hat{M}_J^T$)

$$\hat{L}_J^T \approx -\frac{i}{\sqrt{2}}\frac{g_T}{g_A}\hat{L}_J^A$$

BSM operators

Well known SM operators

$$\hat{C}_J^S \approx -\frac{i}{\sqrt{2}}\frac{g_S}{g_V}\hat{C}_J^V$$

$$\hat{C}_J^P \approx \frac{q}{2m_N}\frac{g_P}{g_A}\hat{L}_J^A$$

Charge	Value
g_A	1.278(33)
g_T	0.987(55)
g_S	1.02(11)
g_P	349(9)

$\frac{g_S}{g_V}, \frac{g_T}{g_A} \sim 1$ nuclear charges

- Predictions & Observables for forbidden decays for the first time

Multipole Expansion

General Theory - for any nucleus & transition

M. Gonzalez-Alonso *et al.*, PPNP 104 165-223 (2019)

AGM & Gazit, arXiv:2207.01357, accepted to Phys. Rev. D (2023)

Multipole operator's matrix elements

$\hat{H}$

Nuclear Hamiltonian

$\hat{\mathcal{J}}(\vec{x})$

SM Nuclear currents

$\hat{\mathcal{J}}(\vec{x})$

BSM nuclear currents

$\langle \psi_f \| \quad \| \psi_i \rangle$

Nuclear wave functions

$\hat{O}_J$

SM Multipole operators

$\langle \psi_f \| \hat{O}_J \| \psi_i \rangle$

SM Nuclear matrix elements

δ_a, δ_b

SM Observables' corrections

BSM predictions

AGM & Gazit, arXiv:2207.01357, in press. Phys. Rev. D (2023)

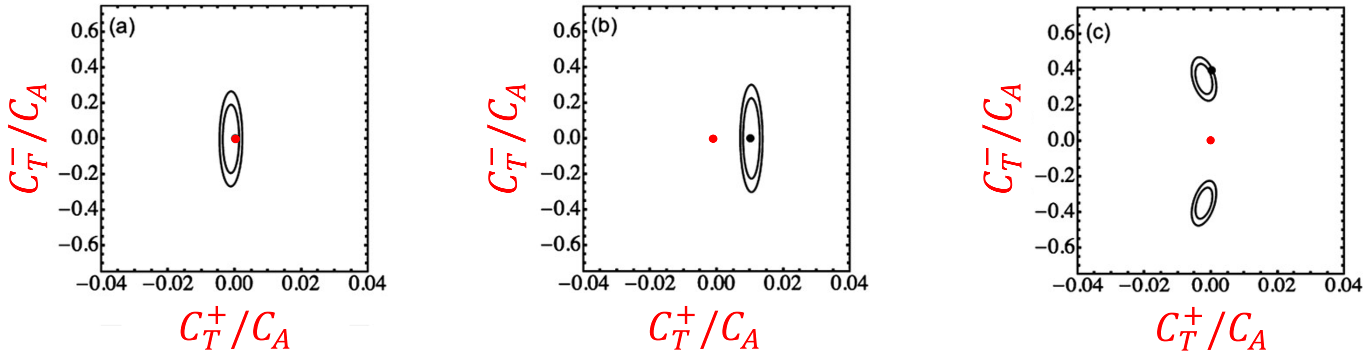
BSM predictions: unique 1st-forbidden decay

$$d\omega \propto 1 + a_{\beta\nu}\left[1 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right] + b_F \frac{m_e}{\epsilon}$$

The β-energy spectrum is sensitive to both $a_{\beta\nu}$ & b_F

- Allows simultaneous extraction of C_T^+ and C_T^-
- Increases the accuracy level

No BSM coupling | Left-handed coupling | Right-handed coupling



Formalism is nice, but applications are nicer…

AGM *et al.*, Phys.Lett.B **767** 285-288 (2017)

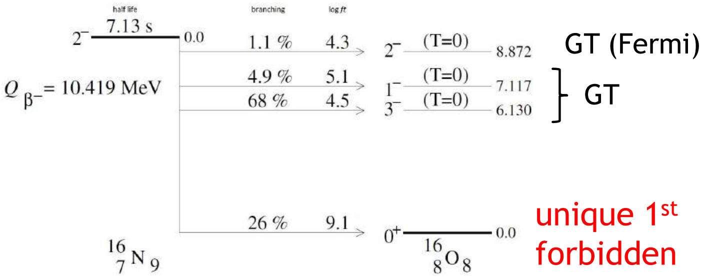
Unique 1st-forbidden experiments

PHYSICAL REVIEW C **105**, 054312 (2022)

Determination of β-decay feeding patterns of ^{88}Rb and ^{88}Kr using the Modular Total Absorption Spectrometer at ORNL HRIBF

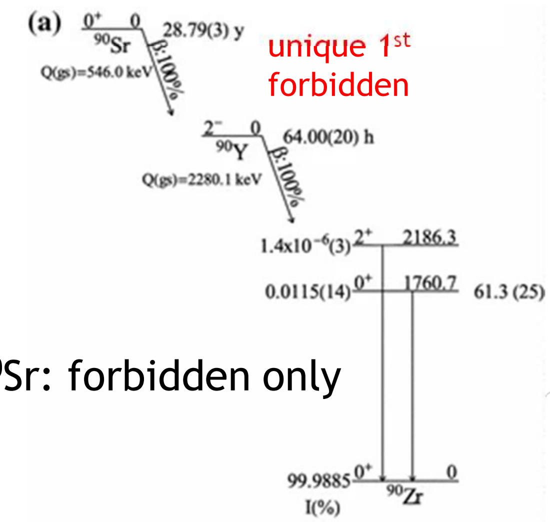
P. Shuai,[1,2,3,4] B. C. Rasco,[1,2,3,*] K. P. Rykaczewski,[2] A. Fijałkowska,[5,3] M. Karny,[5,2,1] M. Wolińska-Cichocka,[6,2,1] R. K. Grzywacz,[3,2,1] C. J. Gross,[2] D. W. Stracener,[2] E. F. Zganjar,[7] J. C. Batchelder,[8,1] J. C. Blackmon,[7] N. T. Brewer,[1,2,3] S. Go,[3] M. Cooper,[3] K. C. Goetz,[9,3] J. W. Johnson,[2] C. U. Jost,[2] T. T. King,[2] J. T. Matta,[2] J. H. Hamilton,[10] A. Laminack,[2] K. Miernik,[5] M. Madurga,[3] D. Miller,[3,11] C. D. Nesaraja,[2] S. Padgett,[3] S. V. Paulauskas,[3] M. M. Rajabali,[12] T. Ruland,[7] M. Stepaniuk,[5] E. H. Wang,[10] and J. A. Winger[13]

^{88}Rb decay spectra suggests that MTAS can distinguish an allowed β spectral shape from a first forbidden unique β spectral shape.



^{16}N: Large energy separation between the forbidden and allowed branches

Ohayon, Chocron, Hirsh, AGM, *et al.*, Hyp.Int.**239**,57 (2018)



^{90}Sr: forbidden only

Fig.: Morozov et al. J.Rad.Nuc.Chem.**284**,221 (2010)

Summary

- Experiments are aiming an accuracy of 10^{-3}
- SM: Theory with controlled level of accuracy
  - Experiments become useful!

- ^{6}He - Corrections with an uncertainty of 10^{-4}
- ^{23}Ne with experimental results
  - New bounds on BSM Tensor interactions

- The BSM missing theory
  - Uses the already-known SM matrix elements
  - Unique 1st Forbidden decays as a new opportunity

Gives significant constraints even for the naivest nuclear calculations

Can be done to any nucleus & decay (allowed/forbidden)

Paving the way for new, even higher precision experiments and discoveries

- Ongoing 1st Forbidden experiments @SARAF (^{16}N, ^{90}Sr), @ORNL (^{88}Rb)
  - Ab initio NCSM Calculations for ^{16}N

- Beyond the impulse approximation
  - Calculating 2-body currents and increasing the theory accuracy

Thanks!

Hebrew University
Doron Gazit
Guy Ron
Hitesh Rahangdale
Vishal Srivastava

TRIUMF
Petr Navrátil
Peter Gysbers
Lotta Jokiniemi

Chalmers University
Christian Forssén

ÚJF rez
Daniel Gazda

University of Barcelona
Javier Menéndez

NCSU
Leendert Hayen

LLNL
Nicholas Scielzo
Yonatan Mishnayot
Jason Harke
Aaron Gallant
Richard Hughes

SARAF (SOREQ)
Sergey Vaintraub
Tsviki Hirsh
Leonid Waisman
Arik Kreisel
Boaz Kaizer
Hodaya Dafna
Maayan Buzaglo

ETH Zurich
Ben Ohayon

Weizamnn Institute
Michael Hass

Ministry of Science and Technology, Israel
Israeli Science Foundation (ISF)
European Research Council (ERC)