The X17 with chiral couplings

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Phys.Rev.D 113 (2026) 11, 11

PIKIMO 21
Pittsburgh, Pennsylvania
November 7, 2026

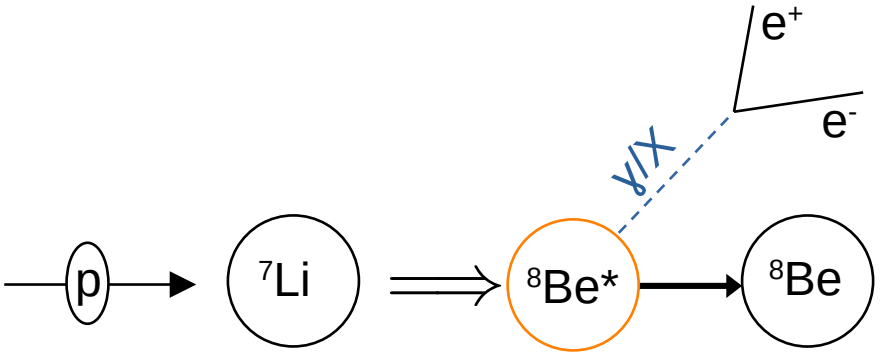
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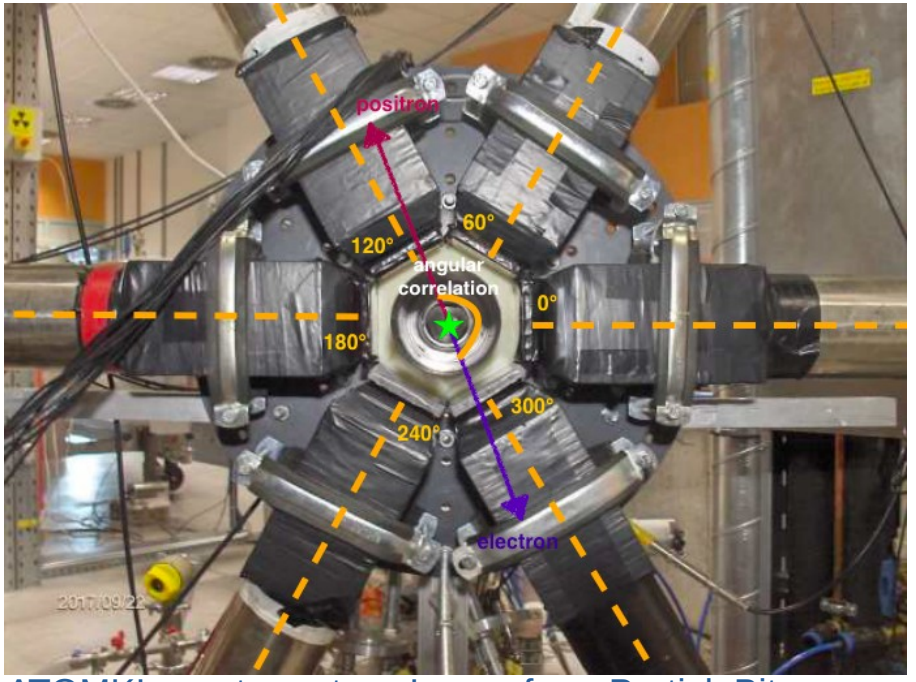
The ATOMKI anomaly

- ATOMKI observes nuclear de-excitations
  $$N^* \to N + \gamma \to N + e^+ + e^-$$
- Probes θ(e^+e^-) in ^{4}He, ^{8}Be, ^{12}C
- Excesses e.g.
  - ^{8}Be(18.15) ~140°
  - ^{4}He(20.49) ~115°

Resonance peak E above g.s. [MeV]

- Explanation: ~17 MeV boson?
- Also seen in VINATOM, no significant observation in MEG II
  - Interest reinvigorated by PADME results JHEP 11 (2025) 007
    - Completely different experiment: positron annihilation on target





ATOMKI spectrometer - Image from ParticleBites

Theoretical framework

- Nuclei have different J^P and excitation energies, is one BSM explanation consistent?
  - Scalars incompatible with ground/excited state spin-parity
  - Pseudoscalars incompatible with carbon measurement
  - Previously focus on bosons with purely vector or axial couplings
    - Not encompassing all possibilities of nature, contrasting SM (g_A, g_V of Z, W)
- Instead, use EFT at E << m_N allowing general chiral couplings
  - Nucleus fields: ground state N_0, excited state N_* / N_*^μ
    - EFT operators for X^μ interaction
    - Coefficients from matching to measured / nuclear calc. ME
  - At nucleon level:

$$\mathcal{L} = \frac{1}{2} X^\mu \Big[\underbrace{(e\epsilon_p^V + e\epsilon_n^V) J_\mu^0 + (\epsilon_p^A + \epsilon_n^A) J_{\mu,5}^0}_{\text{Isospin: conserved}} + \underbrace{(e\epsilon_p^V - e\epsilon_n^V) J_\mu^1 + (\epsilon_p^A - \epsilon_n^A) J_{\mu,5}^1}_{\text{not conserved}} \Big]$$

Vector Axial

Operators mediating transitions

- Set of possible operators describing X^μ, N, N_* / N_*^μ interactions obtained by considering selection rules for a transition from angular momentum and parity

Spin-parity of excited nucleus

FS orb.ang. momentum

Ground state

$$J_* = L \oplus J_0 \oplus J_X \xrightarrow{J_0^{P_0}=0^+} L \oplus J_X$$

$$P_* = (-1)^L P_0 P_X \xrightarrow{J_0^{P_0}=0^+} (-1)^L P_X$$

G.s. parity

X parity

N_*	$J_*^{P_*}$	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	$\mathcal{O}_{5P}^{(1)}$	$\mathcal{O}_{3S}^{(1)}$, $\mathcal{O}_{5D}^{(1)}$
^{12}C(17.23)	1^-	$\mathcal{O}_{3S}^{(1)}$, $\mathcal{O}_{5D}^{(1)}$	$\mathcal{O}_{5P}^{(1)}$
^{4}He(21.01)	0^-	—	$\mathcal{O}_{4P}^{(1)}$
^{4}He(20.21)	0^+	$\mathcal{O}_{4P}^{(1)}$	—

- Operators for different dimensions & partial waves (S,D,P) are of the form

$$\mathcal{O}_{3S}^{(1)} = \Lambda N_0^\dagger N_*^\mu X_\mu$$

E,g, Mass dim. 3, S-wave, mediated by spin-(1) X

$$\mathcal{O}_{5D}^{(1)} = \frac{1}{\Lambda} N_0^\dagger (\partial_\mu N_*^\nu) \partial_\nu X^\mu$$

$$\mathcal{O}_{5P}^{(1)} = \frac{1}{\Lambda} N_0^\dagger \epsilon^{\mu\nu\alpha\beta} (\partial_\mu N_{*\nu}) \partial_\alpha X_\beta$$

$$\mathcal{O}_{4P}^{(1)} = N_0^\dagger X^\mu \partial_\mu N_*$$

Beryllium

- Two relevant excited state E: ^{8}Be(17.64) (mostly isovector), ^{8}Be(18.15) (~isoscalar)
  Isospin mixing & breaking: c.f. J.L. Feng et.al. Phys.Rev.D 95 (2017) 3, 035017
  - Both excited states 1^{+}

Axial vector interaction $\mathcal{O}_{3S}^{(1)} \implies C_A^{\mathrm{Be}} \Lambda N_0^\dagger N_*^\mu X_\mu$

Vector interaction $\mathcal{O}_{5P}^{(1)} \implies C_V^{\mathrm{Be}} \frac{1}{\Lambda} N_0^\dagger \epsilon^{\mu\nu\alpha\beta} (\partial_\mu N_{*\nu}) \partial_\alpha X_\beta$

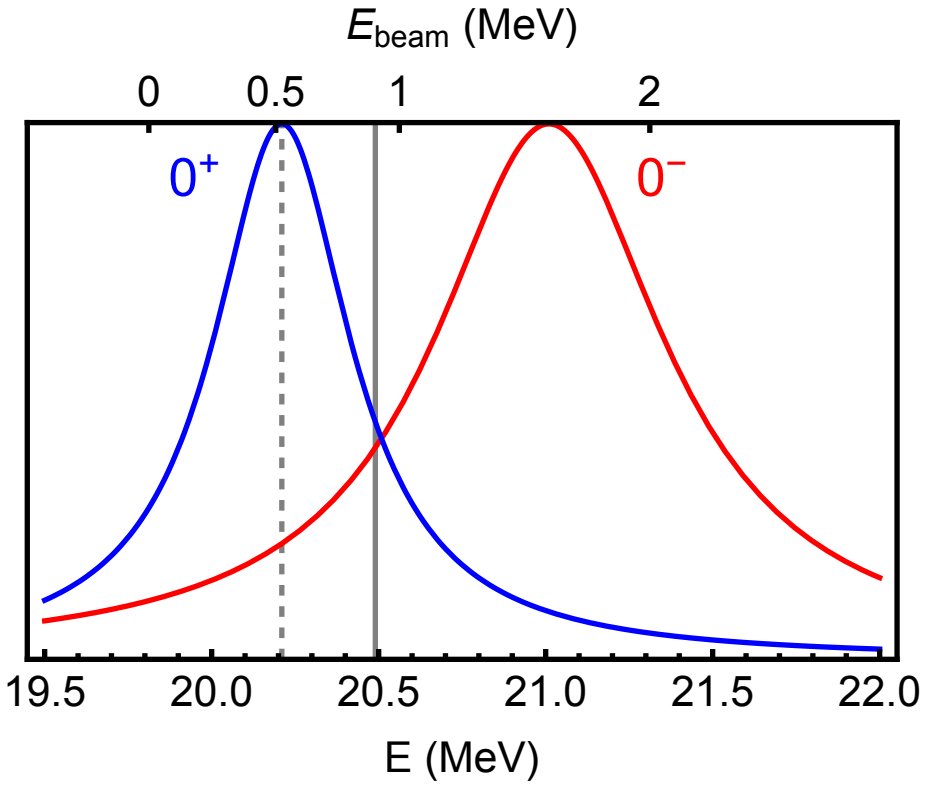
- **Vector**
  - ME from measured photon decay width
    - Mediated by same currents

- **Axial vector**
  - ME from many-body calculation J. Kozaczuk et.al. Phys.Rev.D 95 (2017) 11, 115024
  - See also P. Gysbers et.al. Phys.Rev.C 110 (2024) 1, 015503

Helium

- Measurement between two resonances
  - Consider a mixed state
    - He(20.21) => Vector
    - He(21.01) => Axial vector
- Isospin conserving, common operator

$$\mathcal{O}_{4P}^{(1)} \implies C_{V,A}^{\mathrm{He}} N_0^\dagger X^\mu \partial_\mu N_*$$



J.L. Feng, T.M.P. Tait, C.B. Verhaaren, Phys.Rev.D 102 (2020) 3, 036016

Helium

$$\frac{\sigma_X}{\sigma_{E0}} = \frac{\Gamma(0^+ \to X)}{\Gamma_{E0}} + \frac{0.76\Gamma_-}{\Gamma_+}\left(\frac{(E_{\rm CM}^2 - M_+^2)^2 + M_+^2\Gamma_+^2}{(E_{\rm CM}^2 - M_-^2)^2 + M_-^2\Gamma_-^2}\right)\frac{\Gamma(0^- \to X)}{\Gamma_{E0}}$$

Bound state full widths

- **Vector** from He(20.21), 0^+
  - Cannot match EFT vertex to ɣ decay (0^+ scalar to $m_ɣ$=0 forbidden)
  - Operator with X related to SM decay (E0, photon off shell) via X EOM: $C_{E0} = C_V^{\rm He}\frac{\Lambda^2}{m_X^2}$
- **Axial vector** from He(21.01), 0^-
  - Matrix element from 4-body simulation: W. Horiuchi, Y. Suzuki Int.J.Mod.Phys.A 24 (2009) 2134-2141
    - Pointed out in D. Barducci, C. Toni JHEP 02 (2023) 154 JHEP 07 (2023) 168
  - No uncertainty given!
    - Use 50% and 100% as benchmarks

Carbon

- Excited state 1^-, isospin not conserved
- **Vector** $\mathcal{O}_{3S}^{(1)} \implies C_{V,C}\Lambda N_0^\dagger N_*^\mu X_\mu$

  $\mathcal{O}_{5D}^{(1)} \implies C_{V,C}^{(5)}\frac{1}{\Lambda}(N_*^\nu \partial^\mu N_0^\dagger - N_0^\dagger \partial^\mu N_*^\nu)(\partial_\nu X_\mu - \partial_\mu X_\nu)$

  - Matching: replacing X^μ by A^μ yields a non-gauge-invariant operator
    - Leading photon operator as in O_5
    - At LO in v_X^2, dimension 3 & 5 operators related: $C_{3V}^{\mathrm{C}} = C_{5V}^{\mathrm{C}}\frac{m_N E_X}{\Lambda^2}$
- **Axial vector** $\mathcal{O}_{5P}^{(1)} \implies \frac{C_{A,C}}{\Lambda}N_0^\dagger \epsilon^{\mu\nu\alpha\beta}(\partial_\mu N_{*\nu})\partial_\alpha X_\beta$
  - Matching to ME calculated in particle-hold shell model
    - Related to ɣ decay width: $\Gamma_\gamma^{\mathrm{pred}} = 5.4\,\Gamma_\gamma^{\mathrm{exp}}$
    - Benchmark effect of uncertainties: 50%, 100%; also consider a factor 5 shift

Evading constraints

- Rare π decay at **SINDRUM-I** spectrometer constrains $\mathcal{B}(\pi^+ \to e^+ \nu_e X) < 10^{-9}$
  - Decay rate proportional to charge difference ΔQ_X
    - To evade, X needs an electron coupling related to quark couplings
      - Tuned to cancel X production in π decay: demand $\Delta Q_X = 0$

$$|\Delta Q_X|/e = |(e\epsilon_u^V + \epsilon_u^A) - (e\epsilon_d^V + \epsilon_d^A) - \underbrace{(e\epsilon_\nu^V - \epsilon_\nu^A)}_{=0} - (e\epsilon_e^V - \underbrace{\epsilon_e^A}_{=0})|$$

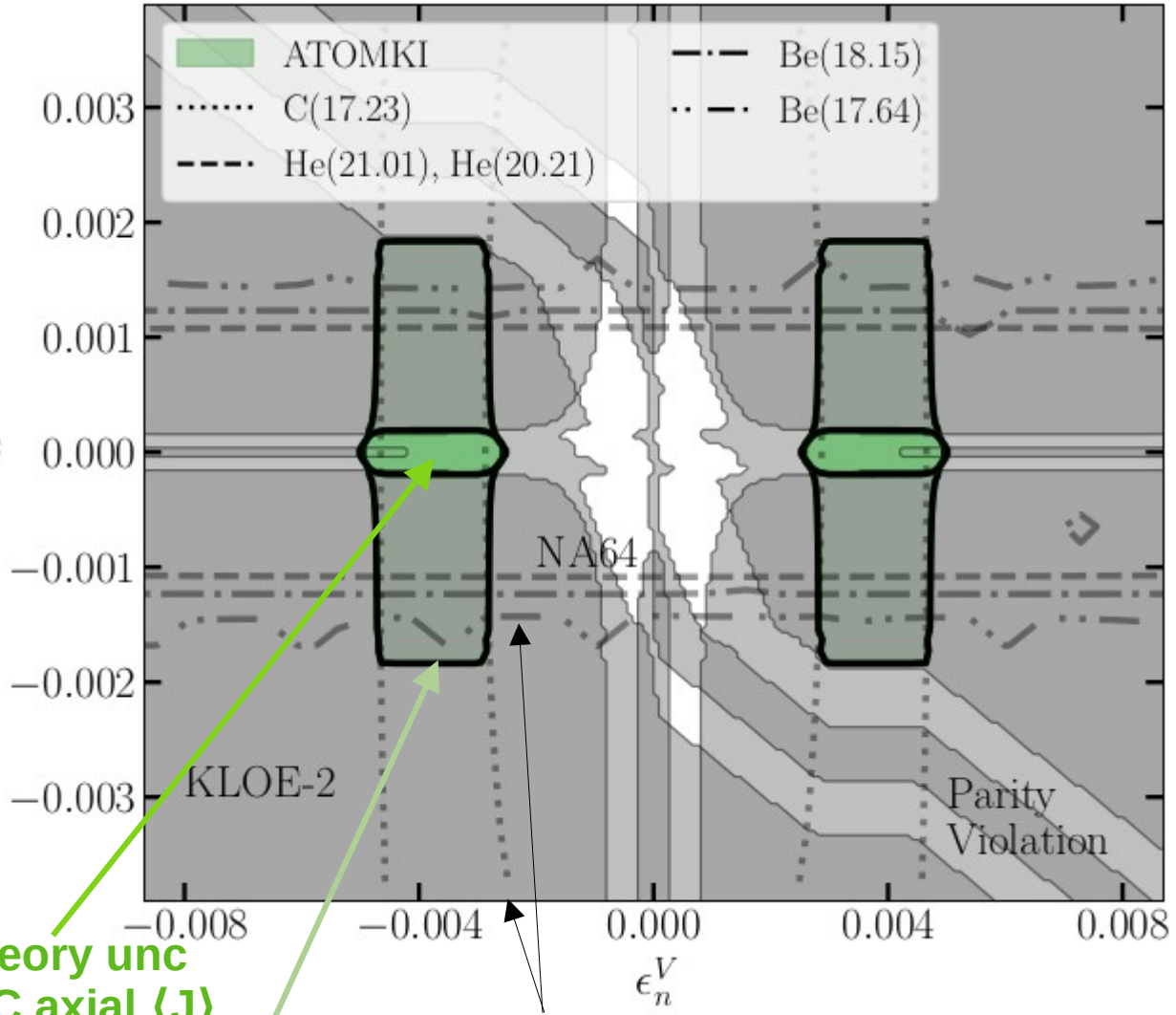
~0.01 to cancel u,d

- However, next need to consider bounds on ε_e^V
  - KLOE-2 $((e\varepsilon_e^V)^2 + (\varepsilon_e^A)^2)^{-1/2} < 2 \cdot 10^{-3}$ e
  - NA64 $\varepsilon_e^V > 6.8 \cdot 10^{-4}$
  - Mixed vector & axial-vector couplings result in parity violation
    - Atomic parity violation (Cs) bounds $\varepsilon_p^A \cdot \varepsilon_N^V$

Results

- Free parameters
  - Fit m_X (ATOMKI only / ATOMKI+PADME)
  - Couplings ϵ_p^V, ϵ_p^A, ϵ_n^V, ϵ_n^A
    - Profile over p couplings
- Fixed parameters

  ϵ_e^V (SINDRUM), $\epsilon_e^A = 0$
- Find regions in ϵ_n^V,ϵ_n^A space in **99% CL agreement with ATOMKI**, compare to **constraints**

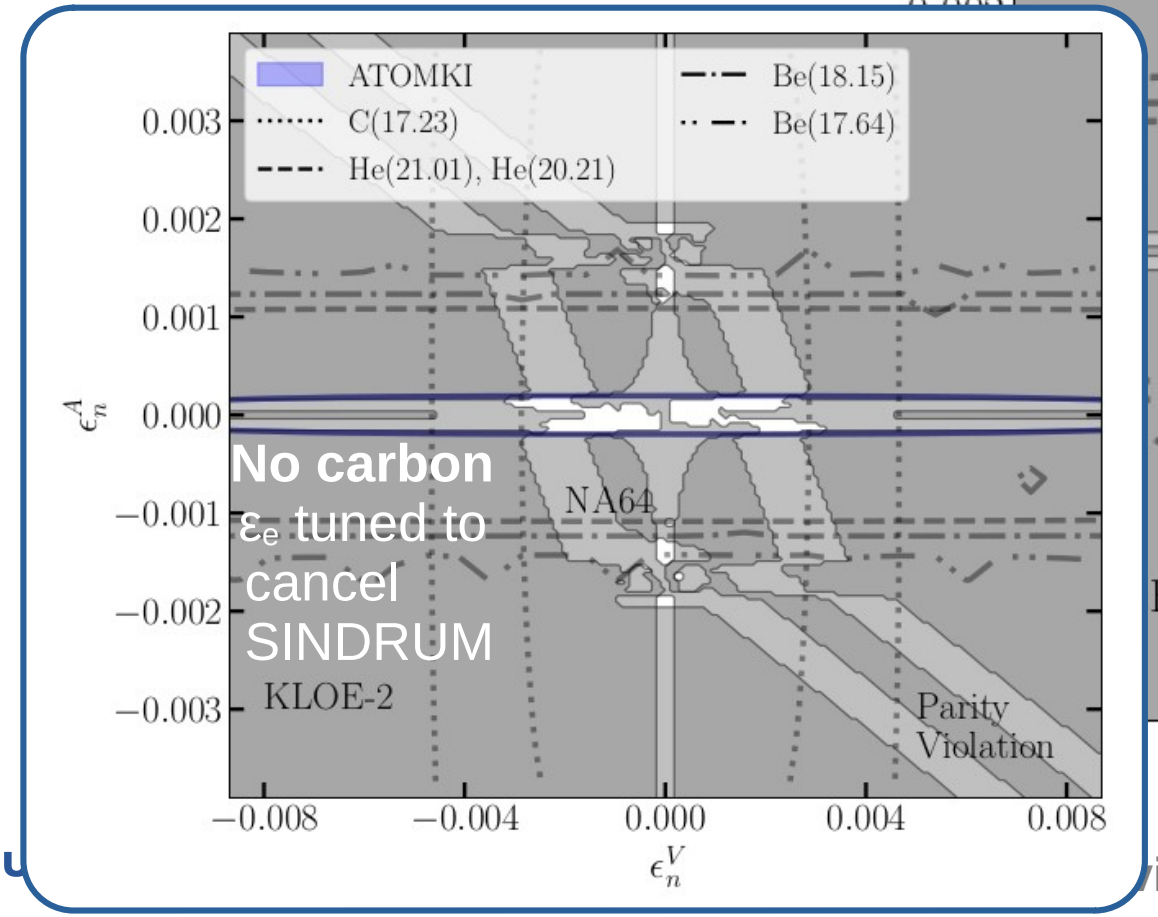


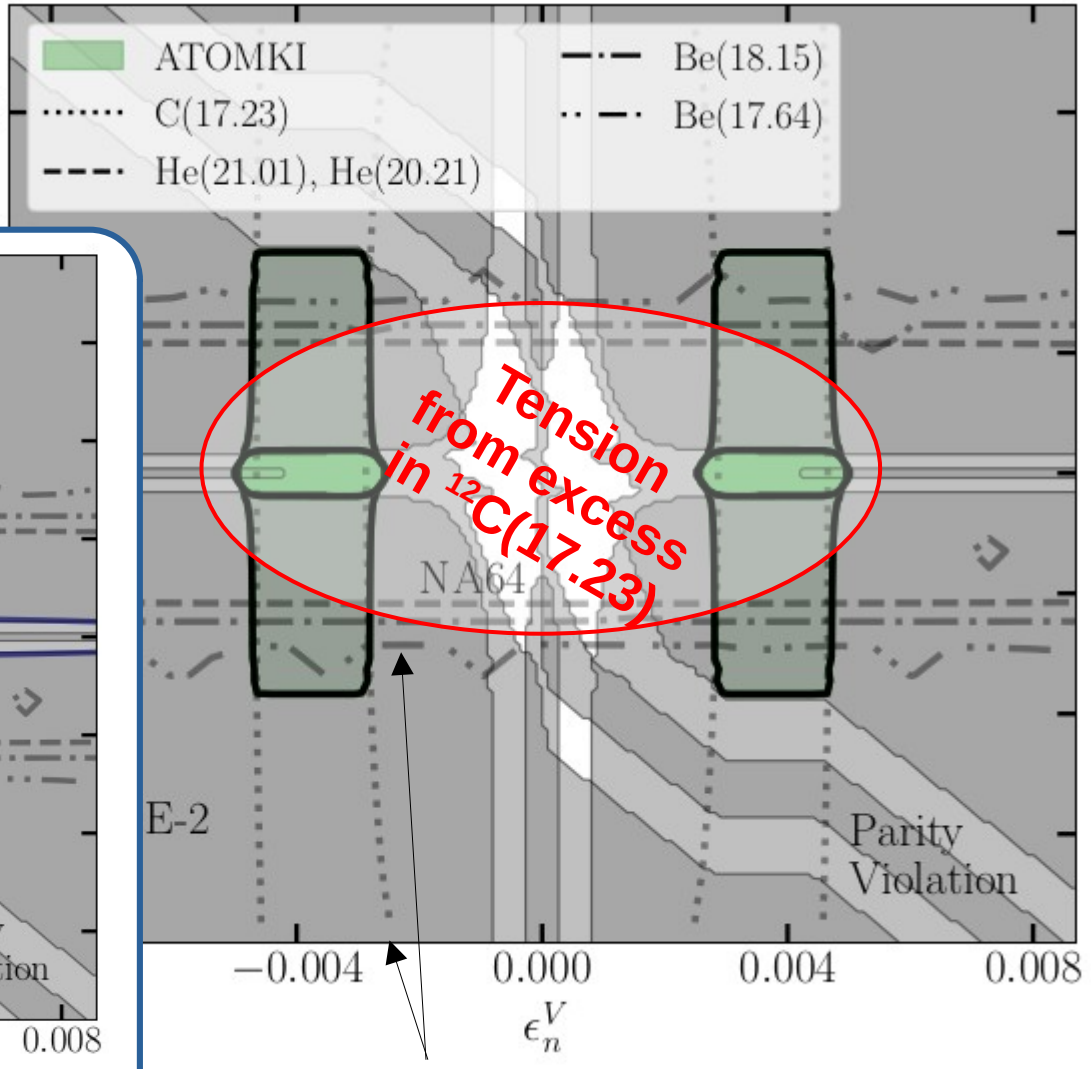
50% theory unc on He,C axial ⟨J⟩

100% uncertainty

Individual measurements $\Delta\chi^2<1$

Results – no carbon

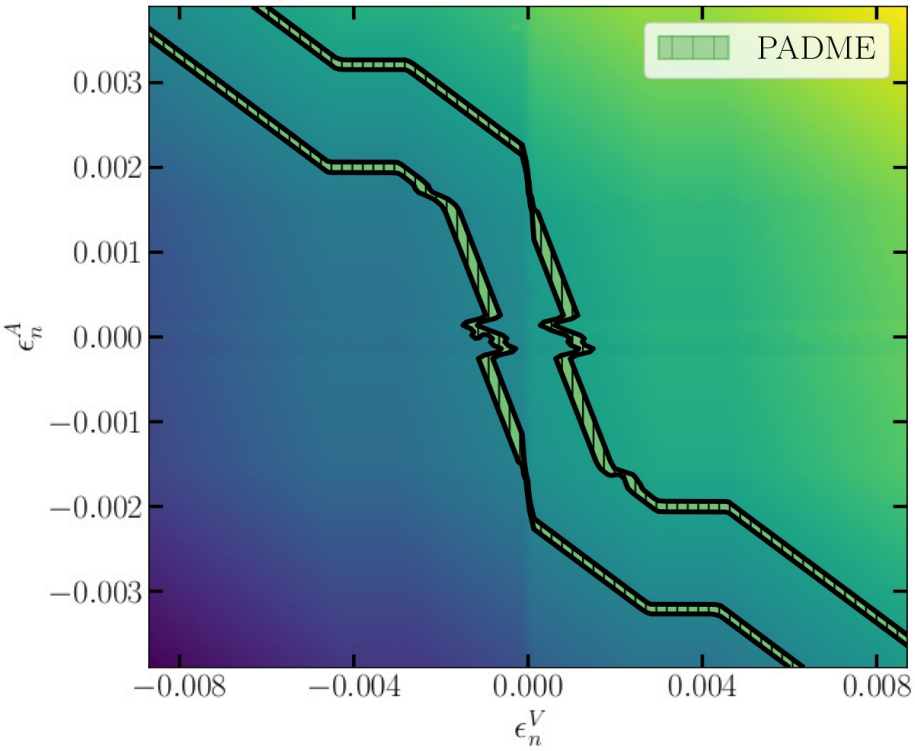


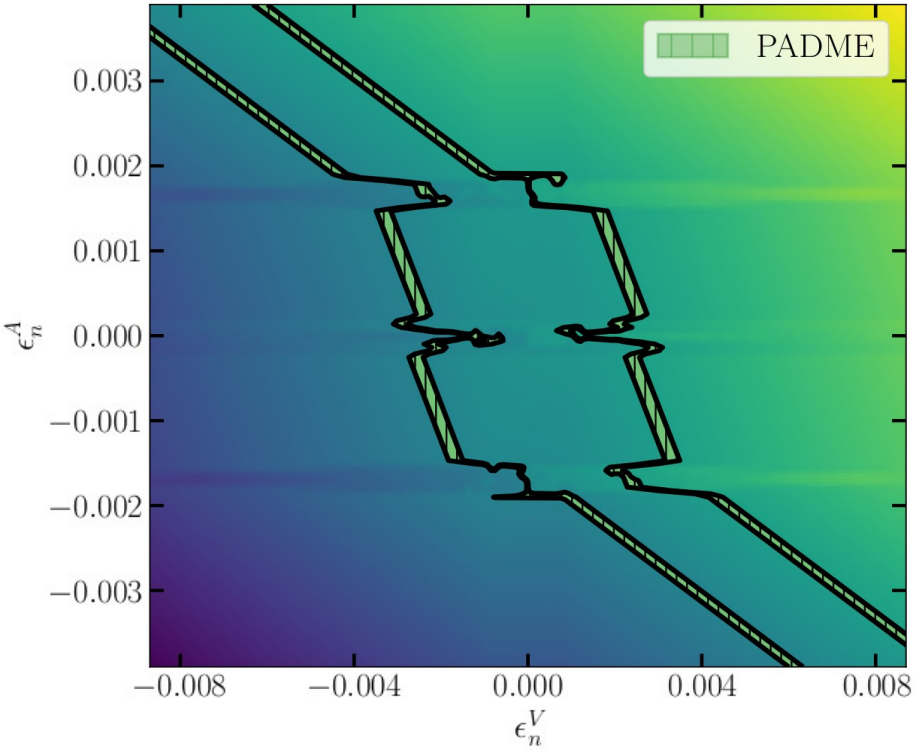


idual measurements $\Delta\chi^2<1$

PADME

Colormap:
high ε_e^V (< 0.015) / low ε_e^V (> -0.015) **No ^{12}C**

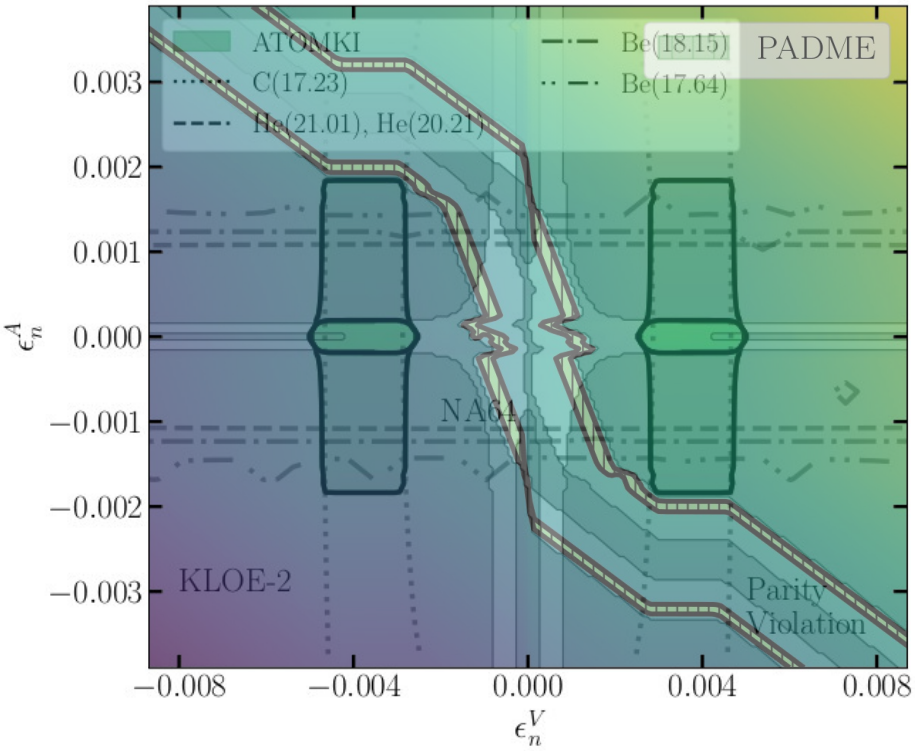


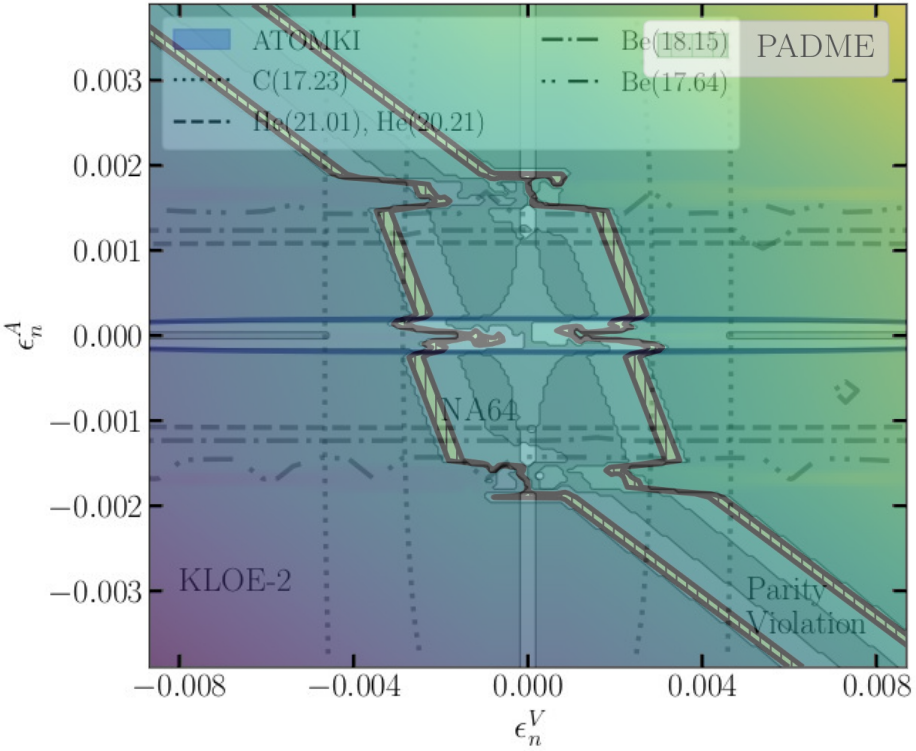


Area within bands compatible with PADME

PADME

Colormap:
high ε_e^V (< 0.015) / low ε_e^V (> -0.015) **No ^{12}C**





Area within bands compatible with PADME

Summary

- Constructed an EFT for an X17 with general vector/axial-vector couplings
  - Agnostic of UV completion
- Difficulties to accommodate all constraints
  - Electron coupling tuned to cancel SINDRUM
- Best fit region is in tension with carbon
  - Some unconstrained parameter space accessible if excluding carbon
    - Carbon measurement + calculations need to be understood better
      - Pseudoscalar hypothesis previously excluded based on carbon!

ThanX for your attention!