Applications of ab initio nuclear theory to tests of fundamental symmetries

Michael Gennari [1,2], Mack Atkinson [3], Chien Yeah Seng [4], Misha Gorchtein [5], Petr Navrátil [2]
[1] University of Victoria [2] TRIUMF [3] Lawrence Livermore National Lab [4] University of Bonn [5] MITP

Cabibbo–Kobayashi–Maskawa matrix unitarity

CKM matrix unitarity is a sensitive probe of the Standard Model (SM). The largest contribution to the top-row unitarity sum – V_{ud} – can be calculated cleanly from Fermi decays, but theoretical corrections to experimental transitions are needed **[1]**. Recent analysis suggests a discrepancy with unitarity **[2,3]** on the order of $2\sigma - 3\sigma$.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0004$$

Fermi transitions

$$\mathfrak{F}t = \frac{K}{G_V^2 |M_{F0}|^2 (1+\Delta_R^V)}$$

- SM requires **nuclear structure dependent** corrections to experiment [1]

$$\mathfrak{F}t = ft(1+\delta_R')(\underline{1-\delta_C+\delta_{NS}})$$

- δ_C – isospin symmetry breaking correction due to isospin non-conserving (INC) interactions, e.g. Coulomb interaction
- δ_{NS} – nuclear environment modifies free nucleon γW-box

We can use the no-core shell model to rigorously evaluate these corrections!

Discovery, accelerated

Precision beta decay in the no-core shell model (NCSM)

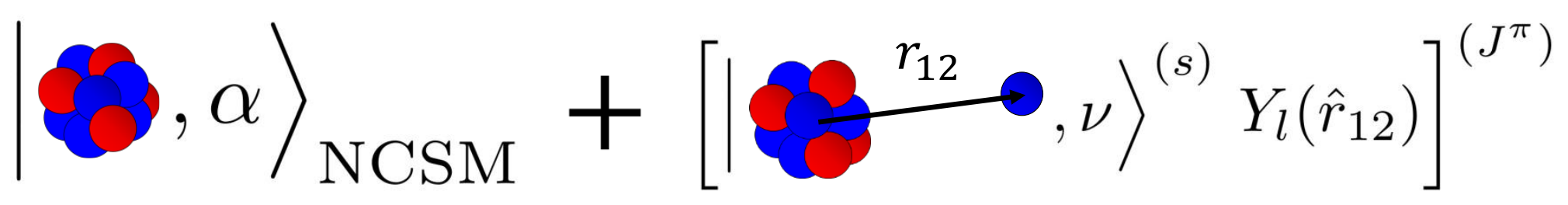
Taking nucleons as the degrees of freedom, ab initio theory describes nuclear structure and reactions, starting solely from inter-nucleon forces. The ab initio NCSM solves the many-body Schrödinger equation for low-lying bound states and resonances [4]. An *ansatz* of antisymmetrized products of harmonic oscillator (HO) many-body states is made:

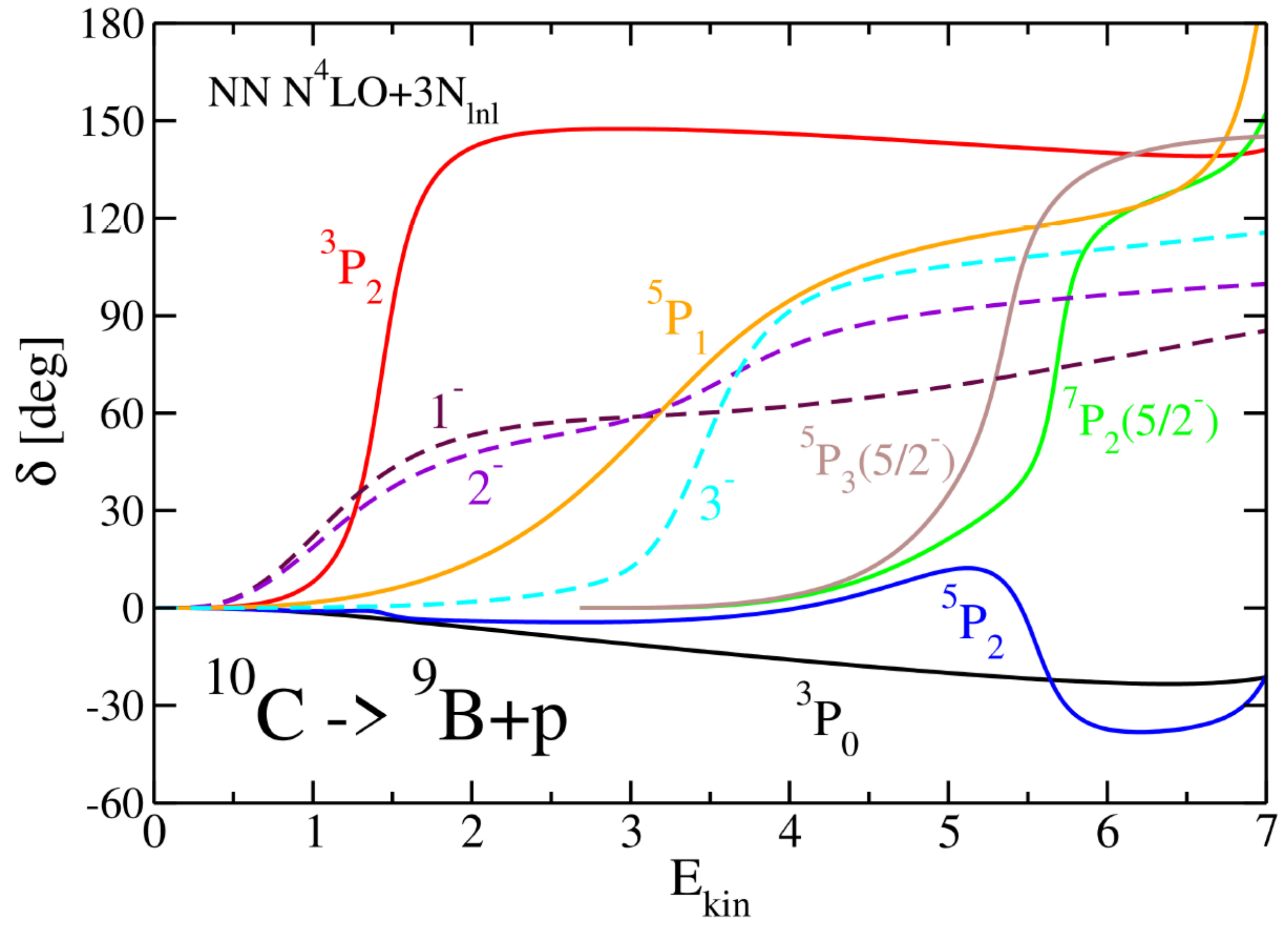
$$H\left|\Psi_A^{J^\pi T}\right\rangle = E^{J^\pi T}\left|\Psi_A^{J^\pi T}\right\rangle \longrightarrow \left|\Psi_A^{J^\pi T}\right\rangle = \sum_{N=0}^{N_{max}} \sum_{\alpha} c_{N\alpha}^{J^\pi T} \left|\Phi_{N\alpha}^{J^\pi T}\right\rangle$$

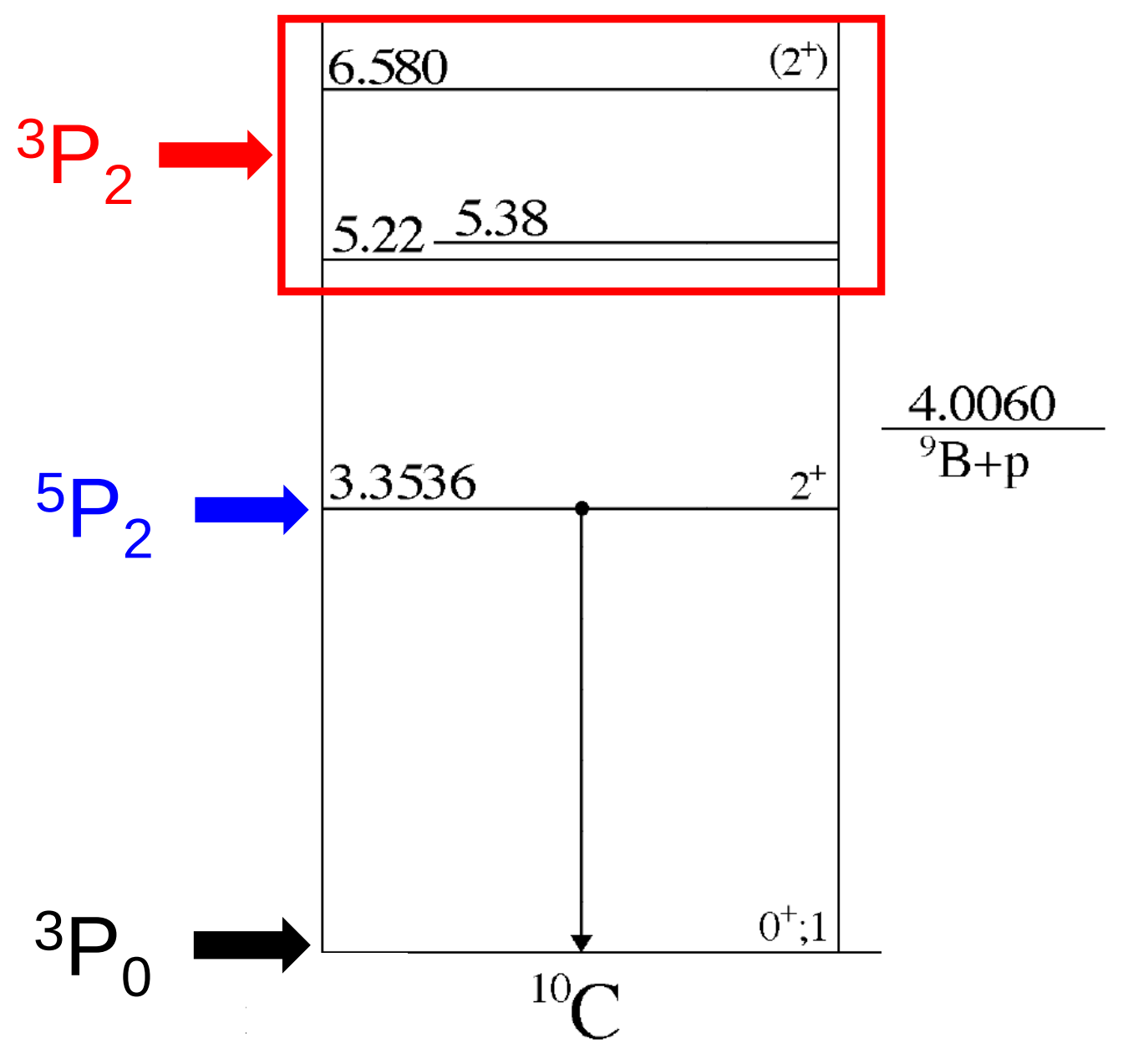
- Galilean invariance preserved but incompatible with reaction theory
- NCSM with continuum (NCSMC) [5] uses *ansatz* of NCSM states plus cluster basis

^{10}C ⟶ ^{10}B Fermi transition

$$|^{10}\mathrm{C}\rangle = \sum_{\alpha} c_\alpha \,|^{10}\mathrm{C},\alpha\rangle_{\mathrm{NCSM}} + \sum_{\nu} \int dr\, \gamma_\nu(r) \mathcal{A}_\nu \,|^{9}\mathrm{B}+p,\nu\rangle$$







	Energy [MeV]		
J$^\pi$	NCSM	NCSMC	Exp.
0^+	−4.75	−3.62	−4.006
2^+	+0.74	−0.11	−0.652

Evaluating δ_C in NCSMC

- Decompose into bound, bound to cluster, and cluster matrix elements
- Contributions factor as one-body matrix elements and J-reduced densities [6]
- Calculations of δ_C for ^{10}C ⟶ ^{10}B in progress

$$M_F = \left\langle \Psi^{J^\pi T_f M_{T_f}} \middle| T_+ \middle| \Psi^{J^\pi T_i M_{T_i}} \right\rangle \longrightarrow |M_F|^2 = |M_{F0}|^2(1-\delta_C)$$

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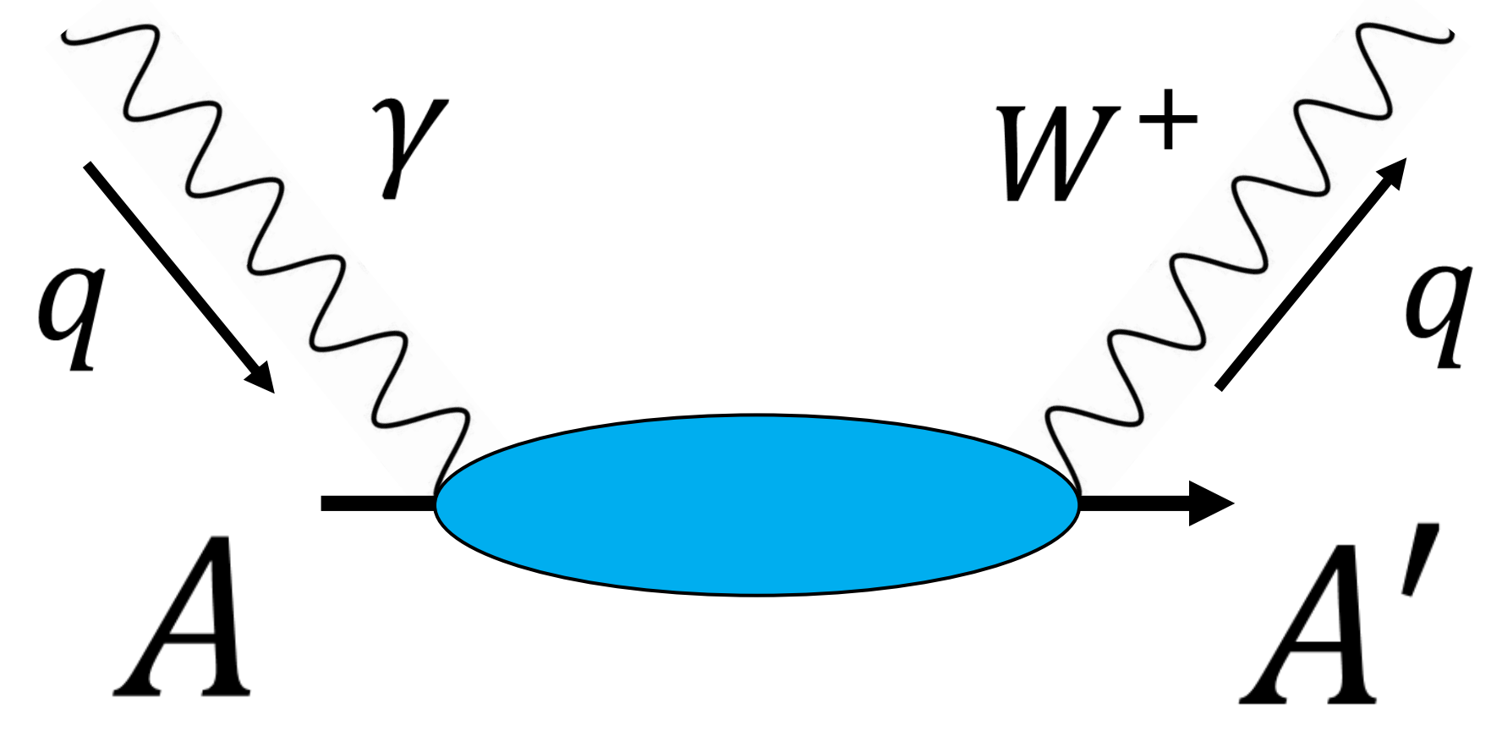
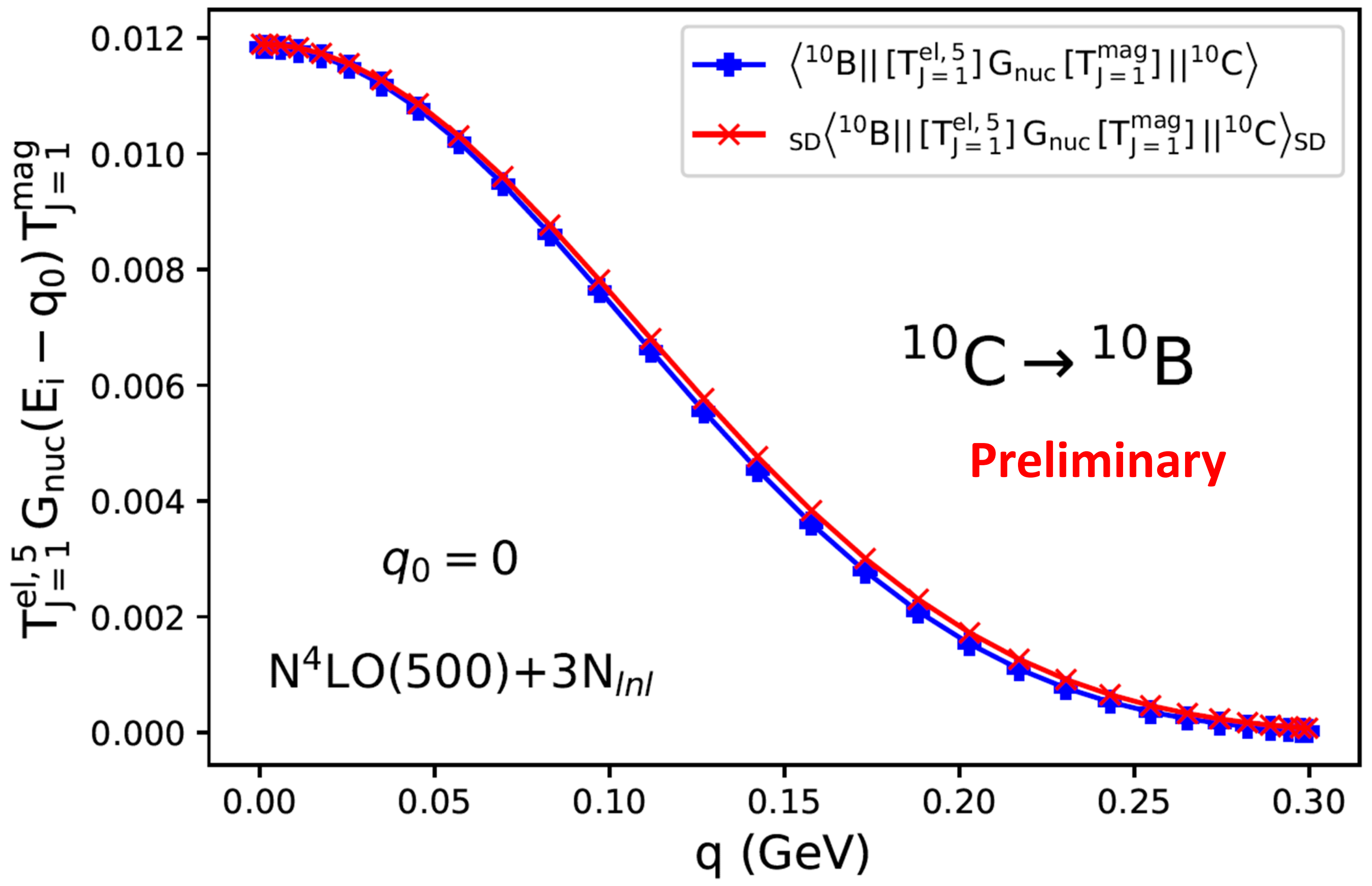


Evaluating δ_{NS} in NCSM

$$T^{\mu\nu,\mathrm{nuc.}}(p,q) = \frac{1}{2}\int d^4x\, e^{iq\cdot x} \langle \phi_f(p) | T\left[J^\mu_{\mathrm{em}}(x) J^\nu_W(0)^\dagger\right] | \phi_i(p) \rangle$$

- Multipole expansion of currents yields four electroweak structures, e.g. $\left[\mathrm{T}^{\mathrm{el},5}(E-H)^{-1}\mathrm{T}^{\mathrm{mag}}\right]$
- Compute q-dependent matrix elements using NCSM eigenstates
- Combine with dispersion integral framework [2,3] for full evaluation of δ_{NS}



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