Charge-Dependent Nucleon–Nucleon Interactions in Covariant Chiral Effective Field Theory

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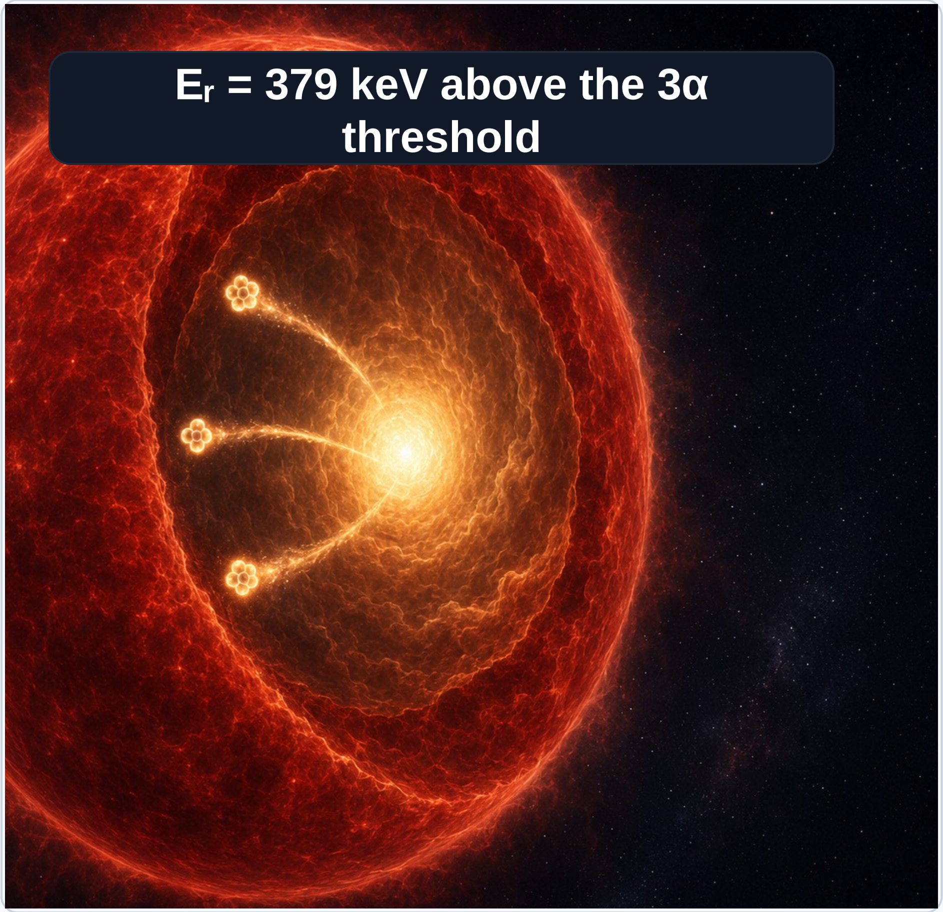
Nuclear forces set the 379-keV gateway to stellar carbon

Opening story

The triple-alpha rate is controlled by where the Hoyle state sits relative to the three-α threshold.



NUCLEAR HAMILTONIAN → 379-keV RESONANCE → STELLAR CARBON

Nuclear Hamiltonian $H = T + V_{NN} + V_{3N} + V_{\mathrm{EM}}$

The Hamiltonian fixes the Hoyle-state energy relative to the 3α threshold

Hoyle state 0_2^+

$E_x(0_2^+) \simeq 7.65\ \mathrm{MeV}$

$$E_r = 379.47\ \mathrm{keV},$$

$$E_r = E(0_2^+) - 3E_\alpha$$

three-α threshold

Rate $r_{3\alpha} \propto T^{-3} \exp[-E_r/(k_{\mathrm{B}}T)]$ (narrow-resonance approximation)

Ab initio EFT describes the Hoyle state

Epelbaum • Krebs • Dean Lee • Meißner

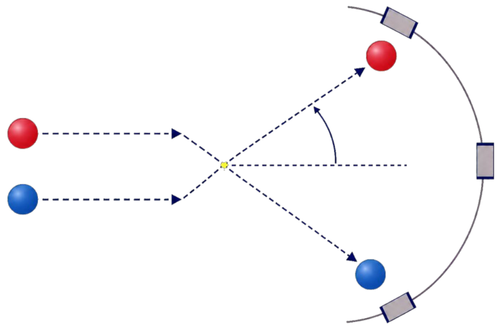
PRL 106, 192501 (2011) · NNLO includes 3N forces · Dean Lee — invited speaker

Precise nuclear interactions must place the Hoyle state correctly relative to the 3α threshold.

Nuclear forces connect scattering to nuclear phenomena

Measure NN scattering → construct microscopic forces → predict nuclear phenomena.

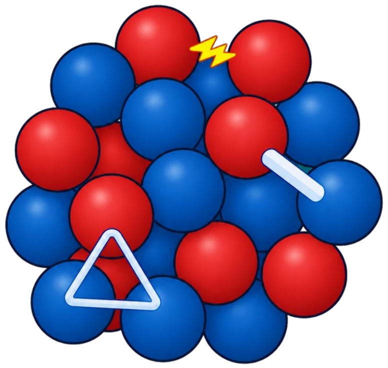
1. Measure NN scattering



Measured cross sections & phase shifts

Data constrain the interaction.

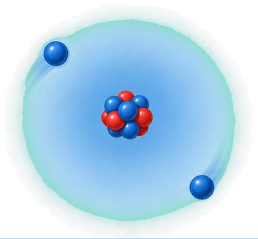
2. Build microscopic forces



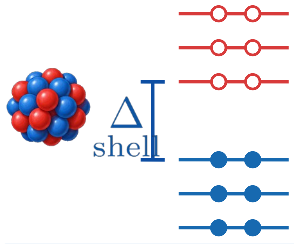
NN + AN(A>=3) + EM

common input for nuclear calculations

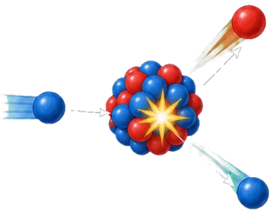
3. Predict nuclear phenomena

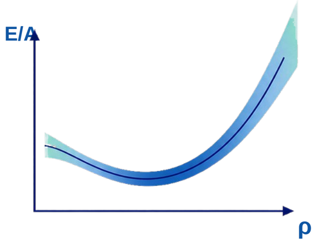


weak binding & halos



shell gap & spectra





reactions

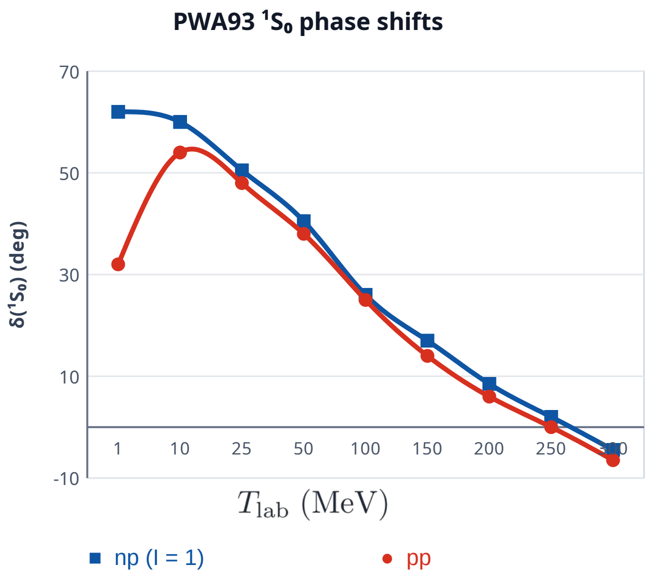
SNM saturation

This talk focuses on one precision component: charge-dependent NN forces.

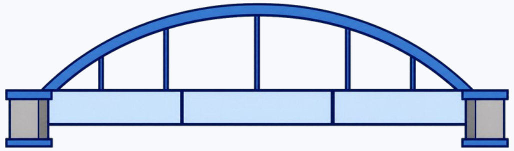
Why charge dependence matters

NN data require charge dependence; finite-nucleus observables test its consequences.

Two-body requirement



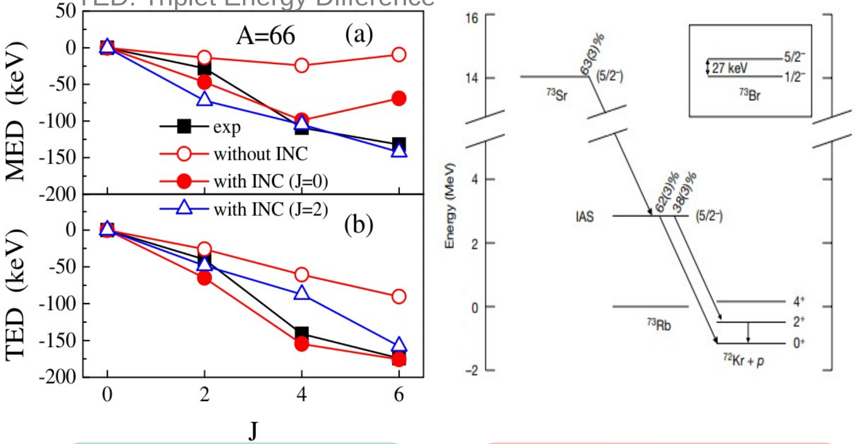
Data from NN-Online



Many-body calculation

Finite-nucleus consequences

MED: Mirror Energy Difference
TED: Triplet Energy Difference



- **INC improves the description.**

- **keV splittings expose symmetry breaking.**

INC: isospin-nonconserving nuclear force

Kaneko et al., PRC 89 (2014); Hoff et al., Nature 580 (2020).

Charge dependence is required by NN scattering and becomes visible in precision nuclear observables.

Why chiral EFT—and why covariant?

Chiral EFT connects nuclear forces to QCD symmetries and improves them systematically, order by order.

1 Chiral EFT turns principles into predictions

1 **QCD SYMMETRIES**

Constrain the allowed low-energy operators

$$\mathcal{L}_{\mathrm{QCD}} \longrightarrow \mathcal{L}_{\mathrm{EFT}}$$

2 **ORDER-BY-ORDER EXPANSION**

Corrections are ranked by the scale Q/Λ_χ

$$\mathrm{LO} \longrightarrow \mathrm{NLO} \longrightarrow \mathrm{NNLO} \longrightarrow \cdots$$

3 **ONE CONSISTENT HIERARCHY**

NN forces, AN (A>=3) forces and currents enter together

$$V_{NN} + V_{AN} + J^{\mu}$$

4 **TRUNCATION UNCERTAINTY**

Order-by-order changes estimate missing terms

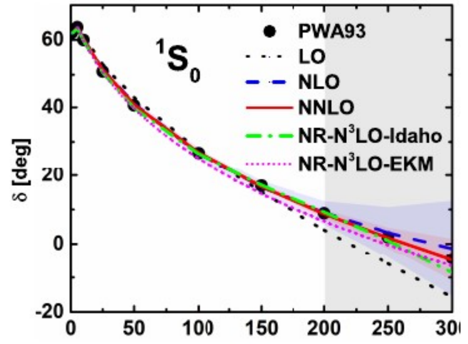
$$X \pm \Delta_{\mathrm{EFT}}$$

Community uptake in ab-initio / first-principles literature (INSPIRE keyword proxy)

367 Chiral N³LO **206 AV18** **124 CD-Bonn**

Entem & Machleidt, PRC 68, 041001(R) (2003) ; Wiringa et al., PRC 51, 38 (1995) ;Machleidt, PRC 63, 024001 (2001)

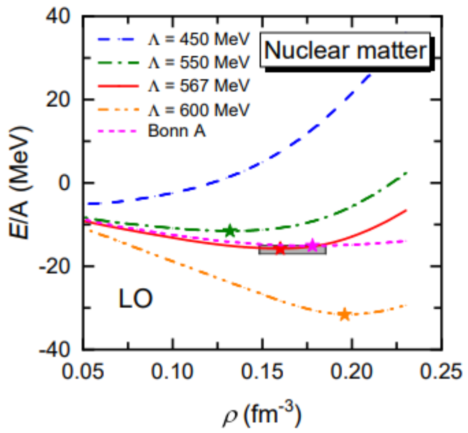
2 Covariance is credible at two scales



TWO-BODY PHASE SHIFTS

- Covariant NNLO describes the empirical phase shift.

Lu, Wang, **Y. Xiao**, Geng, J. Meng, & Ring, PRL (2022).



MANY-BODY SATURATION

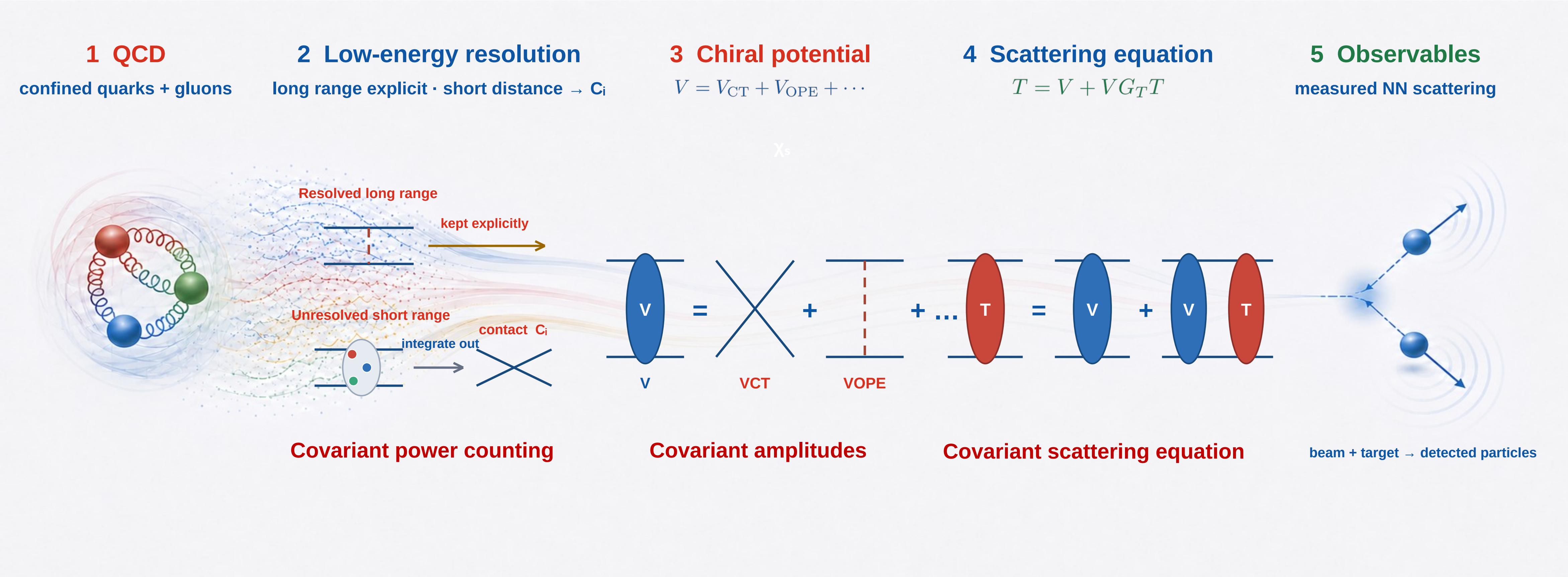
- The covariant NN force reaches the empirical saturation region in RBHF.

Zou, Lu, Zhao, Geng, & J. Meng PLB (2024)
Zou, Yang, Lu, Zhao, Geng, & J. Meng PRC (2026)

Chiral EFT supplies the hierarchy and error control; covariance carries the dynamics from NN scattering to nuclear matter.

How covariant chiral EFT builds an NN force

EFT: High-energy details are encoded in low-energy constants; the low-energy physics remains systematic and testable.



Symmetry fixes the operator basis; low-energy data determine the LECs.

How isospin breaking enters the np/pp interaction

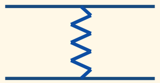
CIB and CSB classify symmetry breaking

ISOSPIN-SYMMETRIC REFERENCE

$$m_u = m_d, \qquad e = 0,$$
$$V_{pp} = V_{np}^{(I=1)} = V_{nn}.$$

WHAT BREAKS THE SYMMETRY IN NATURE?

u ≠ d $\quad m_d - m_u \neq 0$

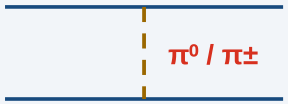


$\mathrm{QED}: \; e \neq 0$ **Both sources feed CIB and CSB operators**

CIB: charge-independence breaking

$$V_{np}^{(I=1)} \neq \tfrac{1}{2}\left(V_{pp} + V_{nn}\right)$$

NLO (ν=2)



$$M_{\pi^\pm} \neq M_{\pi^0}$$

pion mass splitting in OPE · included

CSB: charge-symmetry breaking

$$V_{pp} \neq V_{nn}$$

NLO (ν=2)

$$V_{\mathrm{EM}}^{pp} = V_{1\gamma}^{\mathrm{static}}$$

included

NNLO (ν=3) At NNLO: two distinct short-range choices

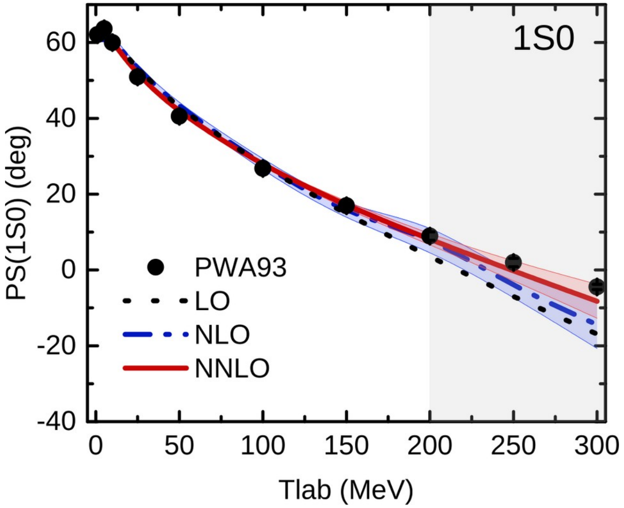
πN-coupling corrections to OPE	**Independent pp contact operators**
Not included here: one common axial coupling is used	Included here: three pp combinations are fitted

Together: a charge-dependent np/pp kernel $\quad V_{np}^{(I=1)} \neq V_{pp}$

Epelbaum et al., Nucl. Phys. A 747, 362 (2005); Reinert et al., Phys. Rev. Lett. 126, 092501 (2021); Y. Xiao et al., Phys.Rev.C 114, 014002 (2026).

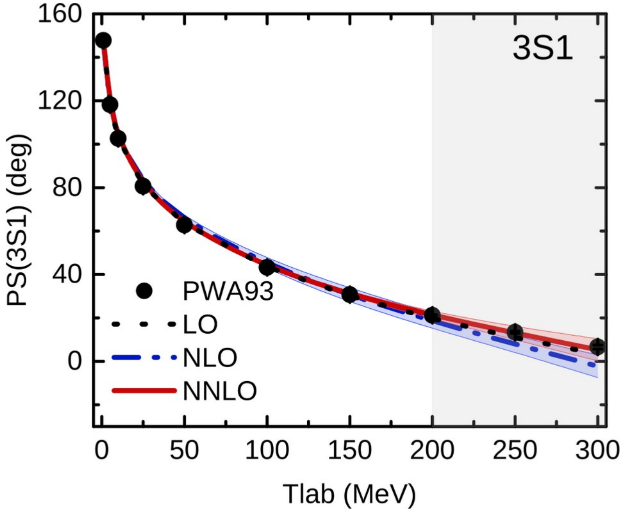
np phase shifts remain well described after introducing charge dependence

Three representative channels



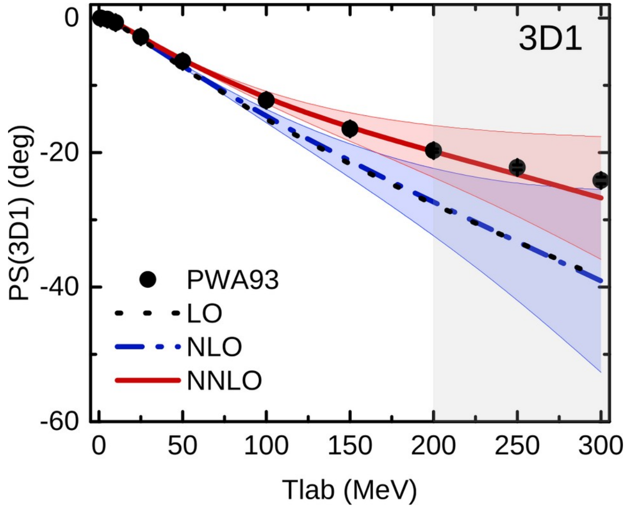
1S0 **low-energy S-wave baseline**

NNLO follows PWA93 across the fitted range.



3S1 **deuteron channel**

The dominant triplet S wave remains accurately described.



3D1 **coupled-channel test**

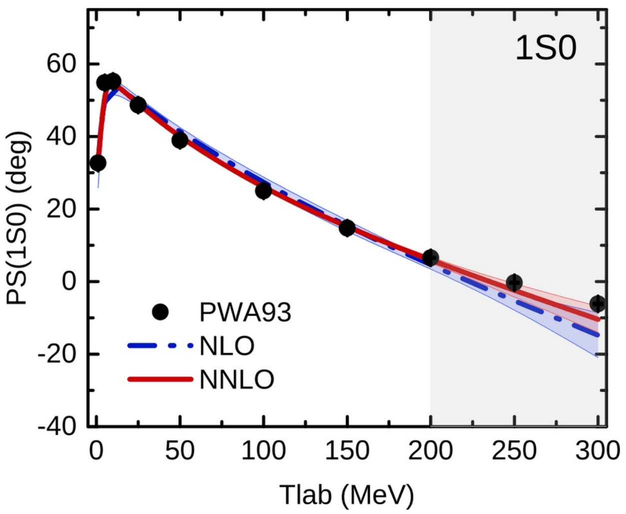
Subleading TPE at NNLO corrects the NLO trend.

Y. Xiao, et al., PRC 114, 014002 (2026)

● PWA93 NLO NNLO

Dots: PWA93; bands: EFT truncation uncertainty; gray: outside the fit range.
The covariant np force provides a controlled isospin-symmetric baseline.

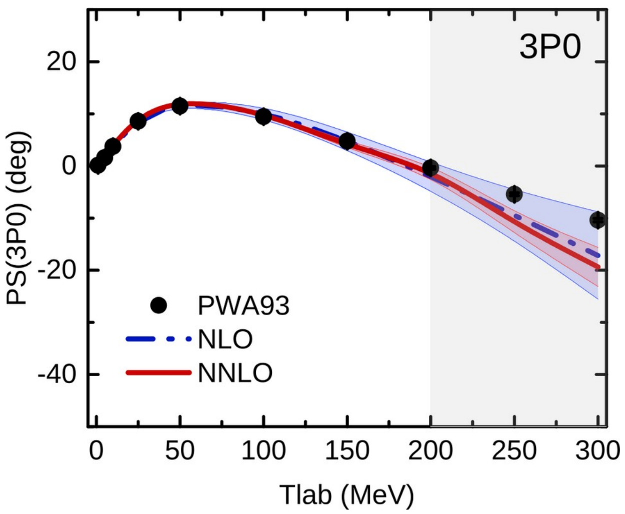
A consistent np/pp description requires a short-range pp correction



1S0: strongest charge-dependent sensitivity

At NLO, Coulomb and pion-mass splitting alone do not fully remove the low-energy np-pp mismatch.

Y. Xiao, et al., PRC 114, 014002 (2026)



3P0: representative P-wave behavior

The curves are already close at low energy;
Differences grow toward the edge of the EFT window.

Contact-off diagnostic

Switch off only additional pp contacts; keep Coulomb and pion-mass splitting unchanged.

Channel	Observed phase-shift impact
$^1S_0$	largest: roughly 3–6° over fitted energies
$^3P_0$	moderate; grows near upper edge of fitted range
$^3P_1$	negligible in this diagnostic

pp short-range correction primarily repairs the low-energy 1S0 channel.

Extending the successful np force to pp requires an additional short-range charge-dependent interaction.

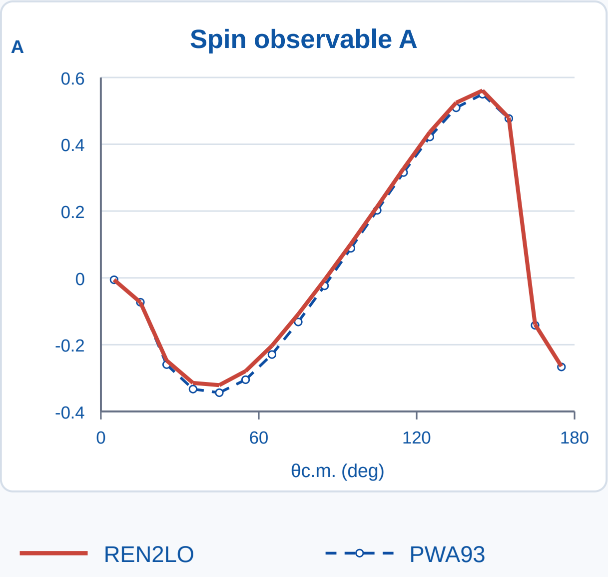
From two-body validation to nuclear applications

First test observables beyond the fitted phase shifts; then carry the interaction into finite nuclei.

1 Validate with physical observables

PRELIMINARY

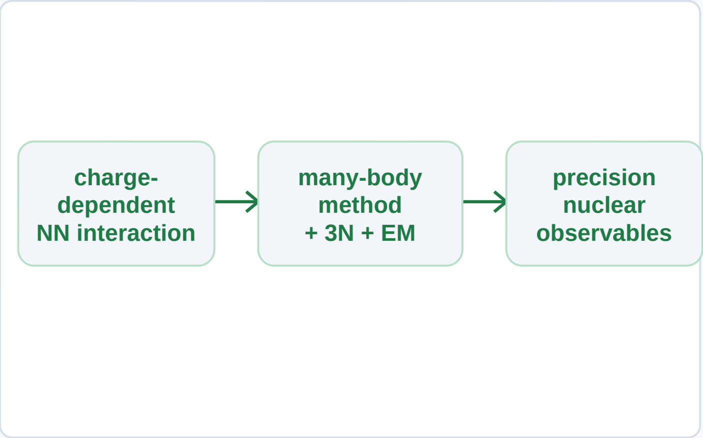
pp · Tlab = 100 MeV



Reproduce spin observables—not only fitted phase shifts.

2 Apply in mirror and exotic nuclei

Use the new charge-dependent NN interaction as a two-body input



Two-body input → many-body calculation → precision observables

Targets: MED/TED · separation energies · spectra · thresholds

Consistent 3N forces, electromagnetic terms, and uncertainty propagation are required.

Near term: validate two-body observables → longer term: precision calculations of mirror and exotic nuclei.

Three take-home messages

1 Isospin-symmetry breaking is visible across nuclear observables

It affects NN scattering, binding and separation energies, excitation spectra, radii, and reaction thresholds—requiring a consistent treatment of charge dependence in precision nuclear theory.

2 A consistent covariant np/pp interaction is constructed through NNLO

Pion-mass splitting, Coulomb, and pp CSB contacts yield a satisfactory simultaneous description of PWA93 phase shifts.

3 The new interaction provides the two-body input for studying isospin-breaking effects in exotic nuclei

Immediate tests include np/pp observables and regulator/EM effects;
The longer-term goal is consistent calculations of mirror and exotic nuclei.

Thank you

Questions?

Backup: chiral EFT versus phenomenological forces

The distinction is the theoretical framework—not simply a smaller NN-data chi-squared.

Question	High-precision phenomenology	Chiral EFT
NN data description	Excellent: AV18 and CD-Bonn are benchmark fits	Excellent at sufficiently high chiral order
QCD information	Not explicit in the organizing principle	QCD chiral symmetry and scale separation constrain the interaction
How to improve	Choose a new ansatz and refit	Add the next order in Q / breakdown scale
Uncertainty	Usually inferred from model spread	Truncation and parameter uncertainties can be quantified
Beyond the 2N force	3N forces and currents are often separate constructions	2N, 3N, 4N forces and currents share one power counting

For ab-initio calculations, chiral EFT makes the Hamiltonian systematically improvable, connects forces with electroweak operators, and supports uncertainty bands for predictions away from fitted data.

Sources: Epelbaum, Hammer & Meißner, RMP 81, 1773 (2009) · Machleidt & Entem, Phys. Rep. 503, 1 (2011)

Backup: what is new in the present work?

The 2022 interaction established the covariant np baseline; the present work adds a controlled pp sector.

Question	Lu et al. PRL (2022)	Present work (2026)
Calibration	np phase shifts	simultaneous np + pp phase shifts
Long range	covariant pion-exchange sector	mass splittings + static V(EM)
Short range	shared isospin-conserving contacts	shared contacts + independent pp CSB correction
Result	accurate covariant NN interaction through NNLO	np quality is retained; low-energy pp $^1S_0$ is improved
Physics role	baseline relativistic two-body force	charge-dependent two-body input for nuclear applications

The new result extends the successful covariant np interaction—it does not replace or refit its physics independently in each channel.

Lu et al., Phys. Rev. Lett. 128, 142002 (2022) · Xiao et al., Phys. Rev. C, accepted (2026), DOI 10.1103/85cd-6gzn

Backup: isospin-breaking terms through NNLO

Dominant isospin-breaking contributions used in the construction

Chiral order	Strong interaction	Electromagnetic interaction
LO ($\nu = 0$)	—	—
NLO ($\nu = 2$)	$M(\pi^\pm) \neq M(\pi^0)$ in OPE	static one-photon exchange
NNLO ($\nu = 3$)	isospin breaking in OPE; nonderivative contact terms	—

Contact convention

$$V_{\mathrm{CT}}^{pp} = V_{\mathrm{CT}}^{(I=1)} + \Delta V_{\mathrm{CT}}^{pp}, \qquad C_{S,V,AV,T}^{pp} \xrightarrow[\text{isospin-symmetric limit}]{} 0$$

Backup: scattering equation and Coulomb treatment

Thompson equation in LSJ basis

$$T^{SJ}_{L'L}(p',p) = V^{SJ}_{L'L}(p',p) + \sum_{L''} \int_0^\infty \frac{k^2\,dk}{(2\pi)^3} V^{SJ}_{L'L''}(p',k) \times \frac{m_N^2}{2(k^2+m_N^2)} \frac{T^{SJ}_{L''L}(k,p)}{\sqrt{p^2+m_N^2} - \sqrt{k^2+m_N^2} + i\epsilon} . \tag{11}$$

Partial-wave phase shifts and mixing angles are extracted from the on-shell S matrix using the Stapp convention.

pp Coulomb treatment

Because pp scattering has long-range Coulomb, the S matrix is formulated in terms of asymptotic Coulomb states using a matching radius R = 12 fm.

Regulator

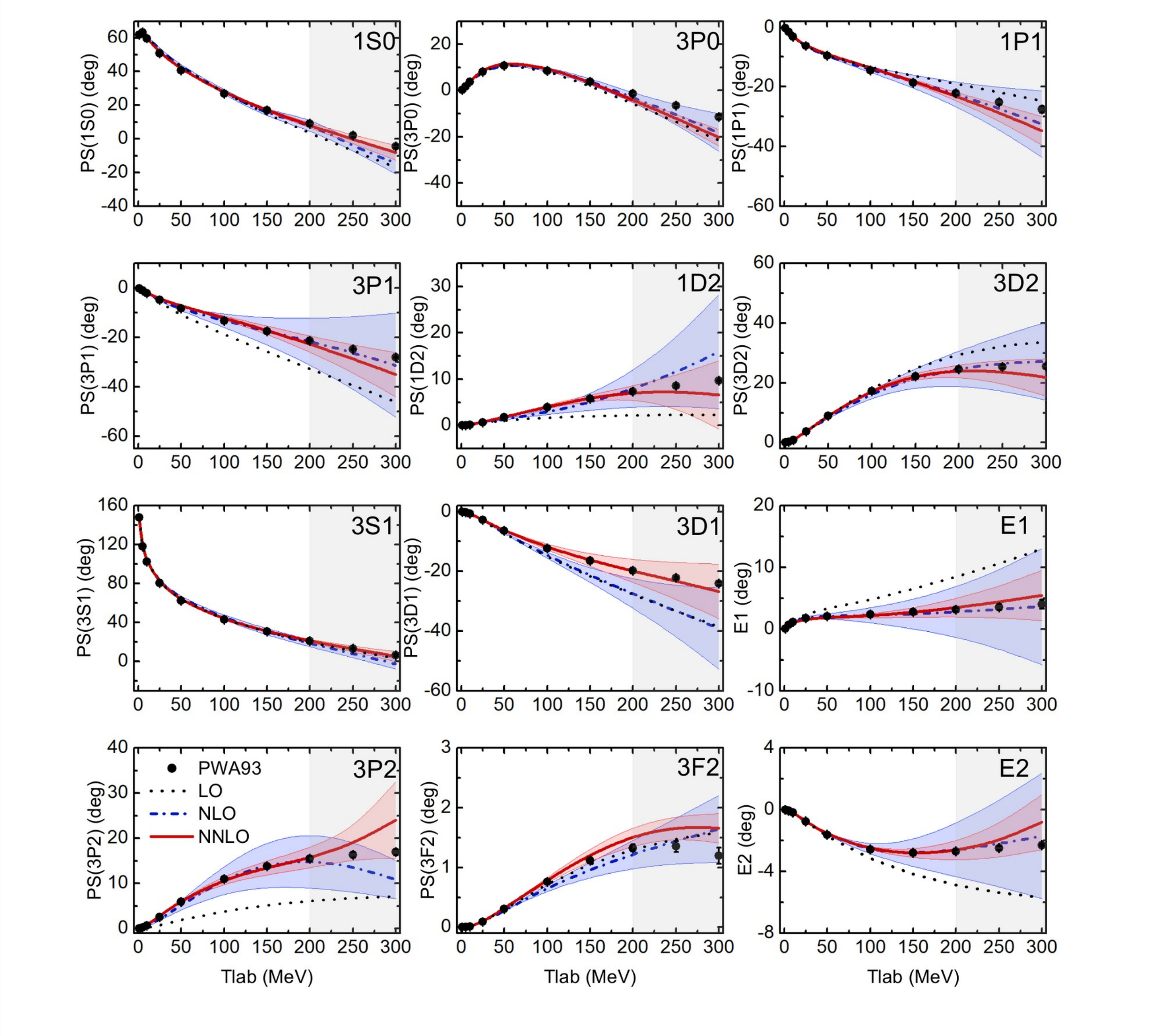
$$f_\Lambda(p,p') = \exp\left[-\frac{p^6+p'^6}{\Lambda^6}\right], \qquad \Lambda = 700\ \mathrm{MeV}$$

Long-range Coulomb is matched consistently to the covariant scattering equation.

Backup: all np phase shifts

All J ≤ 2 partial waves

- Dots: PWA93
- Blue: NLO
- Red: NNLO
- Bands: EFT truncation
- Gray: outside the fit range



Xiao et al., PRC 114, 014002 (2026)

Backup: all pp phase shifts

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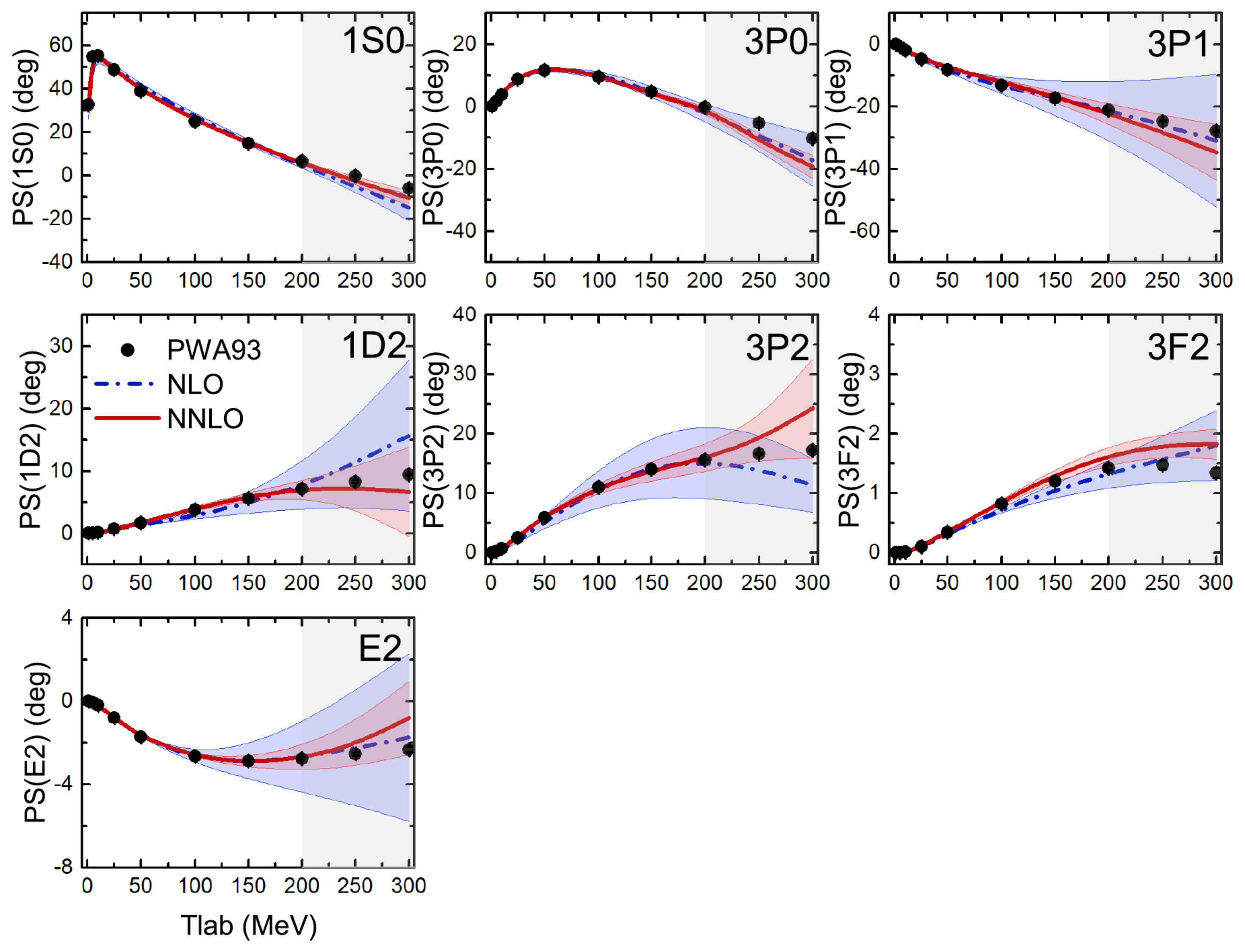


Xiao et al., PRC 114, 014002 (2026)

Backup: fit strategy — shared np/pp physics plus pp corrections

What is fitted?

19 isospin-conserving LECs → **+ 4 pp-channel CSB LECs at NNLO**

Fit target

np and pp phase shifts from PWA93

$$J \leq 2, \qquad T_{\mathrm{lab}} = 1, 5, 10, 25, 50, 100, 150, 200 \ \mathrm{MeV}$$

Regularization

Nonlocal Gaussian regulator

$$\Lambda = 700 \ \mathrm{MeV}$$

Ingredients by channel

Channel	Long range	Short range
np	OPE/TPE with physical pion masses	isospin-conserving contacts
pp	OPE + Coulomb + physical pion masses	isospin-conserving + pp CSB contacts

Interpreting effective χ^2/datum

Here χ^2/datum measures agreement with PWA93 phase shifts; it is not a direct fit to the experimental database.

Scope: np and pp only; no independent nn interaction is fitted.

Backup: fit diagnostics

Effective χ^2 per datum by sector

Sector	NLO	NNLO
total	31.50	7.51
np total	30.36	4.53
pp total	33.46	12.62
np $^1S_0$	14.83	1.33
pp $^1S_0$	181.83	11.41

Selected pp short-range diagnostic

Channel	Effect of setting $C^{pp}(S,V,AV,T) = 0$
$^1S_0$	roughly −3° to −6° over the fitted energies
$^3P_0$	moderate except at the 200 MeV endpoint
$^3P_1$	smaller than 0.01° at all fitted energies

Interpretation

The fitted contact coefficients and the potential kernel are representation- and regulator-dependent; the observables are phase shifts.

Backup: separating the uncertainty budget

An EFT band is not automatically the complete uncertainty of a nuclear prediction.

Source	What it measures	Status in this work
EFT truncation	omitted higher chiral orders	estimated only where an explicit order-by-order band is shown
LEC / fit	parameter uncertainty and correlations	not fully propagated
Regulator	residual cutoff and scheme dependence	one cutoff in the present NN fit; not a full error estimate
Input + EM	PWA93 input and omitted higher EM terms	a separate systematic uncertainty
Many-body	solver, basis and many-body truncations	enters only after the NN force is embedded in nuclei

Backup: why MED/TED isolate CSB/CIB

Energy differences suppress the leading isospin-conserving contribution.

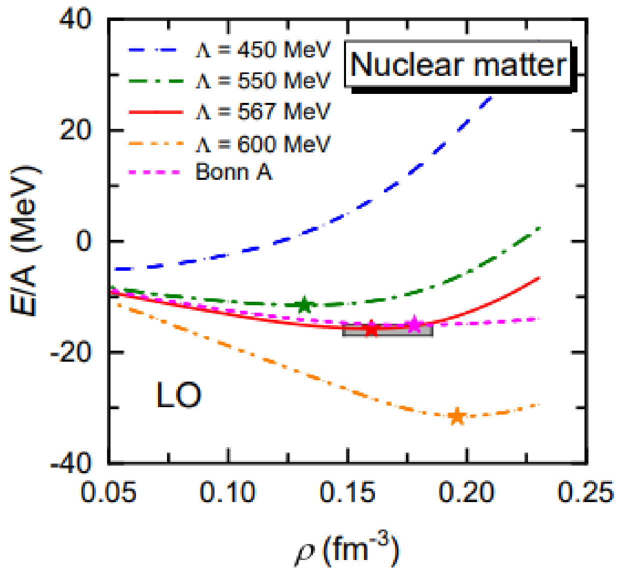
Quantity / idea	Definition	Why it filters CSB/CIB
MED	**Mirror Energy Difference:** $\mathrm{MED}(J) = E_x(J, T_z = -1) - E_x(J, T_z = +1)$	For mirror analogue states, the isospin-conserving Hamiltonian gives the same excitation spectrum after p <-> n. The leftover difference is therefore driven by charge-dependent terms: Coulomb plus CSB nuclear components.
TED	**Triplet Energy Difference:** $\mathrm{TED}(J) = \sum_{T_z=\pm 1} E_x(J, T_z) - 2E_x(J, T_z = 0)$	This second difference cancels the isoscalar part and strongly suppresses first-order isovector shifts. It is therefore especially sensitive to isotensor / CIB components.
Kaneko Fig. 2	A=66 shell-model comparison: experiment vs. EM-only vs. EM+INC nuclear terms.	The EM-only curve captures part of the spin trend, but the magnitude is too small. Adding INC nuclear terms moves the calculation toward the data.
Reference anchors	Kaneko et al., Phys. Rev. C 89, 031302(R) (2014); Hoff et al., Nature 580, 52 (2020); Bentley & Lenzi, Prog. Part. Nucl. Phys. 59, 497 (2007).	Origins of CSB/CIB: Borsanyi et al., Science 347, 1452 (2015); Miller, Nefkens & Šlaus, Phys. Rep. 194, 1 (1990); Epelbaum et al., NPA 747, 362 (2005).

Core idea

Mirror and triplet differences cancel most of the large isospin-conserving energy, leaving a keV-scale signal sensitive to charge-dependent terms.

Backup: what the saturation result does

Evidence: a covariant force can work in RBHF



Zou et al., Phys. Lett. B 854, 138732 (2024): LO covariant NN force in RBHF.

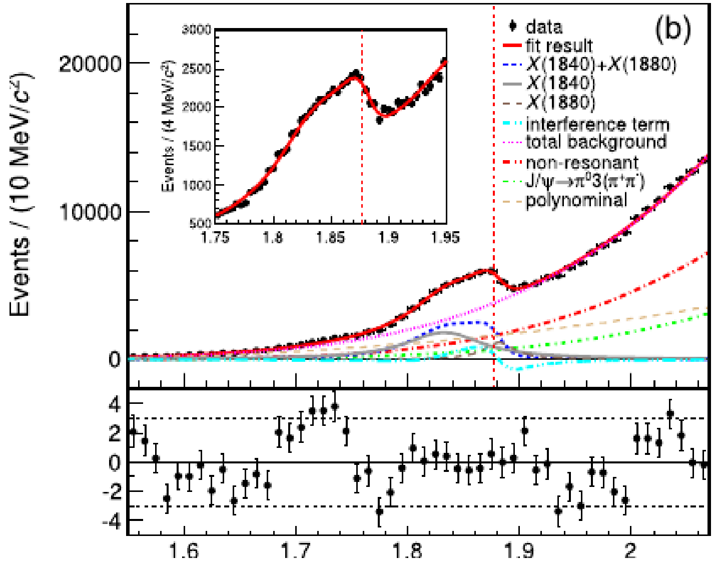
Interpretation boundary

WHAT IT ESTABLISHES

Within an LO RBHF calculation, a covariant two-body force can reach the empirical symmetric-matter saturation region.

Backup: BESIII and antinucleon–nucleon input

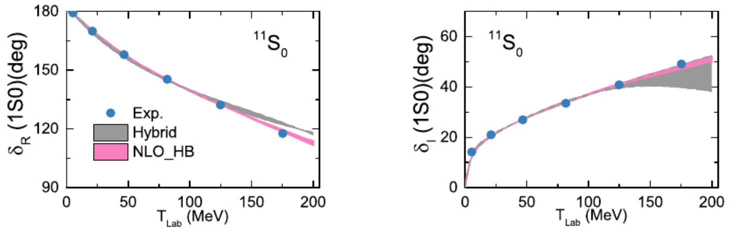
BESIII: anomalous line shape near p p̄ threshold



PRL 132, 151901 (2024), Fig. 3(b): coherent X(1840)+X(1880) fit near p p̄ threshold.

Representative proton–antiproton phase shifts

Y. Xiao, Lu, & Geng, PRC (2024)



Only the $^{11}S_0$ channel is shown; the complete antinucleon–nucleon analysis contains additional partial waves.

Current status: the elastic sector is covariant, whereas the annihilation sector is taken from a heavy-baryon construction.

Next step: fit scattering and production line shapes simultaneously, then test pole stability through analytic continuation.