Ab-initio studies of few-nucleon reactions of astrophysical interest

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Outline

[Microscopic] *ab-initio* studies of few-nucleon reactions of astrophysical interest

- Introduction: when an approach is
  - microscopic
  - *ab-initio*
- Theoretical ingredients:
  - Nuclear interaction
  - Electroweak nuclear currents
- Nuclear reactions of astrophysical interest:
  - reactions of interest for stellar evolution models (SSM)
  - reactions of interest for Big Bang Nucleosynthesis
- ... and beyond:
  - reactions of interest for energy production via nuclear fusion
- Conclusions and outlook

Introduction: microscopic *ab-initio* studies (I)

$\boxed{\text{Nuclear observable X}}$

Cross section of $A_1 + A_2 \to A + \gamma$

Cross section/polarization obs. for electron scatt. off $^A X$

$\ldots$

- Phenomenological *Cluster* methods $\Rightarrow$ sometimes the only way
  - Nucleus = system of clusters depending on the considered situation
  - $^6\mathrm{Li} \equiv {}^4\mathrm{He} + {}^2\mathrm{H}$ or $^6\mathrm{Li} \equiv {}^4\mathrm{He} + n + p$
  - $^7\mathrm{Be} \equiv p + {}^6\mathrm{Li}$ or $^3\mathrm{He} + {}^4\mathrm{He}$
  - "Model-dependent" predictions
- *Microscopic* methods
  - Nucleus = system of A nucleons
    - interacting among themselves $\to$ **structure**
    - interacting with external electroweak probes $\to$ **reactions**

Introduction: microscopic *ab-initio* studies (II)

$\boxed{\text{Microscopic} \rightarrow \textit{ab-initio}}$

Ingredients:

1. realistic description of nuclear interactions [fixed]
2. realistic description of electroweak currents [fixed]
3. exact (*ab-initio*) method to solve the quantum-mechanical problem [only controllable approximations are allowed]

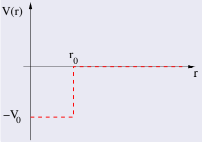
$\Rightarrow$ $\boxed{\text{True predictions for observable X}}$

Ideal case: robust procedure to estimate the theoretical error

Exact means ... ($A = 2$ bound state, $E = -B_d$)

$$\Psi(r) = \frac{u(r)}{r} \quad \longrightarrow \quad u''(r) - \frac{m}{\hbar^2}[V(r) + B_d]u(r) = 0$$

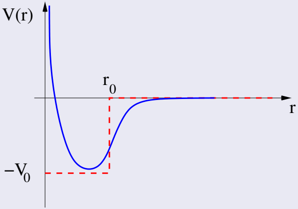
Square well → analytical solution



$$u(r) = C_{>}\mathrm{e}^{-\alpha r} \qquad r > r_0 \qquad \text{where } \alpha = \sqrt{mB_d/\hbar^2}$$

$$u(r) = C_{<}\sin(kr) \qquad r < r_0 \qquad \text{where } k = \sqrt{m(V_0 - B_d)/\hbar^2}$$

Realistic potential → numerical solution



Numerical algorithms:

- Numerov method [accurate for $A = 2$]
- **Expansion on a given basis**
- ...

... and the nuclear interaction is much more complicated!

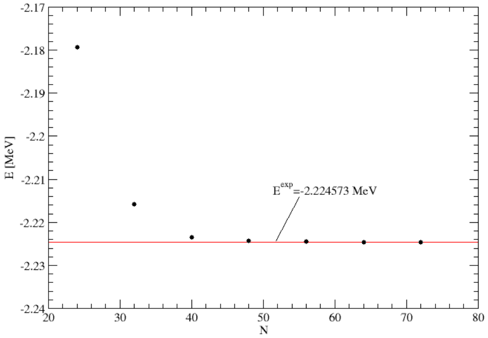
Expansion on a given basis

$$\Psi(\boldsymbol{r}) = \sum_{\mu} c_\mu L_\mu(r)\mathcal{Y}_\mu(\hat{\boldsymbol{r}}) = \sum_{\mu}^{N} c_\mu \phi_\mu$$

- ϕ_μ: known functions vs. c_μ: unknown coefficients
- Rayleigh-Ritz var. principle $\Rightarrow$ eigenvalue-eigenvector problem $\Rightarrow$ c_μ & E

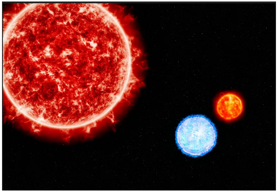
$$\delta_c \langle \Psi(\boldsymbol{r}) | H - E | \Psi(\boldsymbol{r}) \rangle = 0$$

- Phenomenological potential AV18



The nuclear Hamiltonian

$$H \;=\; \sum_i \frac{p_i^2}{2m} + \sum_{i<j} \boldsymbol{V}_{ij} + \sum_{i<j<k} \boldsymbol{V}_{ijk} + \cdots$$



- Non-relativistic approach $\longrightarrow \frac{p_i^2}{2m}$
- Nucleons interact in pairs $\longrightarrow \boldsymbol{V}_{ij}$
- Nucleons are not point-like: the presence of nucleon k changes the shape of nucleons i, j $\longrightarrow \boldsymbol{V}_{ijk}$ (same as the Earth-Moon-Sun system)
- Empirical evidence of V_{ijk}: $B(A>2)_{th} < B(A>2)_{exp}$ with only V_{ij}
- Empirical evidence of no $V_{ijkl}, \ldots$

History: phenomenological approach

Theoretical framework until $\simeq$ 20 years ago

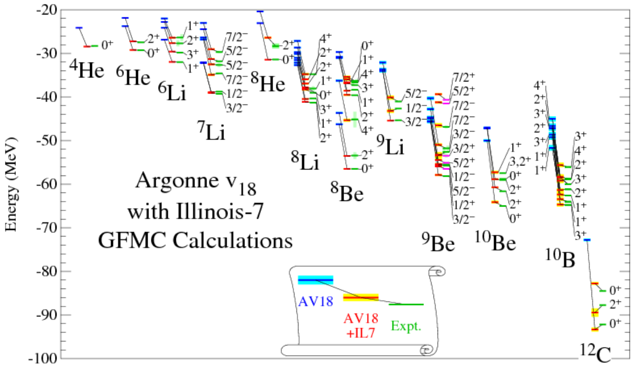
- $V_{ij} \to$ AV18

$$V_{ij} = \sum_{p=1}^{18} f_p(r_{ij}) O_p(\hat{\boldsymbol{r}}_{ij})$$

- $O_p(\hat{\boldsymbol{r}}_{ij})$: **18 operators dictated by theory+data**. They are:

$$[\mathbb{I}, (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j), S_{ij}, \boldsymbol{L} \cdot \boldsymbol{S}, \boldsymbol{L}^2, \boldsymbol{L}^2(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j), (\boldsymbol{L} \cdot \boldsymbol{S})^2] \otimes [\mathbb{I}, (\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)]$$
$$+ T_{ij}, T_{ij}(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j), T_{ij}S_{ij}, (\tau_{i,z} + \tau_{j,z})$$
$$S_{ij} = 3(\boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}}_{ij})(\boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}_{ij}) - \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \;\; \& T_{ij} = 3\boldsymbol{\tau}_{i,z}\boldsymbol{\tau}_{j,z} - \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$

- $f_p(r_{ij})$: **functions with $\simeq$ 40 parameters**, fitted to $A = 2$ experimental data $\to$ χ^2/datum $\simeq 1$
- $V_{ijk} \to$ UIX or IL7: typically **much simpler model**, with 2-3 parameters fitted to $B(A = 3, 4)$



J. Carlson *et al.*, Rev. Mod. Phys. **87**, 1067 (2015)

Very successful, but ...

- **no connection with physics of hadrons (QCD)**
- **difficult to estimate the theoretical uncertainty**
- **mild connection between potentials and currents**

$\longrightarrow$ **Chiral Effective Field Theory (ChEFT)**

Chiral Effective Field Theory (ChEFT)

Nuclear physics

- low-energy QCD
- nuclear force = residual color force

QCD

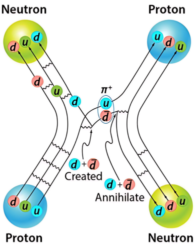
- DOF: quarks, gluons
- non-Abelian theory

  $\Downarrow$

  non-perturbative at low energies

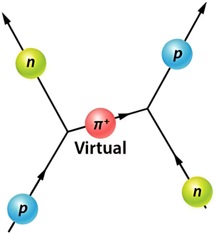
ChEFT

- DOF: nucleons, pions, (Δ-isobar)



QCD

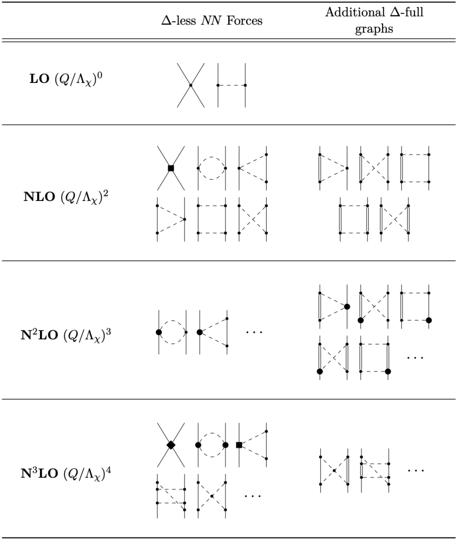
$\gtrsim 1$ GeV



ChEFT

~ 100 MeV

Two-nucleon interaction



- Lagrangian consistent with low-energy **QCD symmetries**

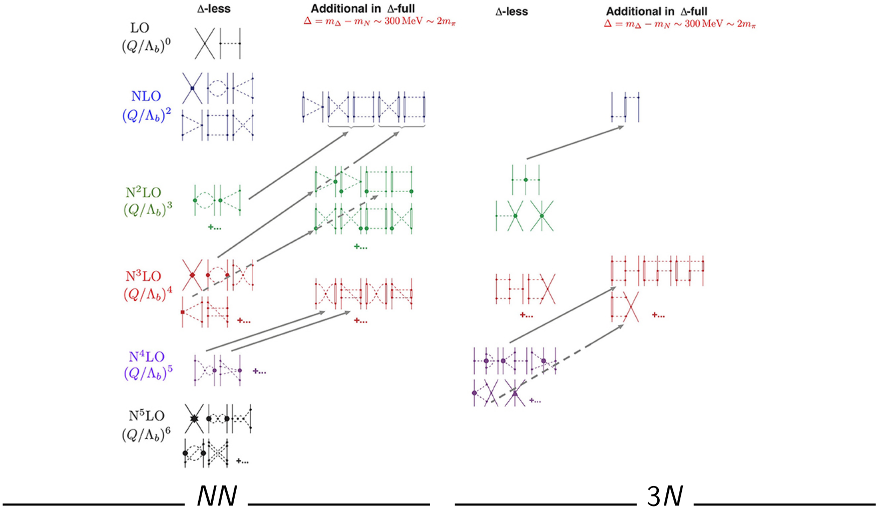
$$\mathcal{L}_{\text{ChEFT}} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + (\mathcal{L}_{\pi N \Delta})$$

- **low-momentum expansion** in terms of Q/Λ_χ

$$Q \sim m_\pi \qquad \Lambda_\chi \sim m_\rho$$

- high-energy DOF $\Longrightarrow$ **contact terms**
- LECs $\Longrightarrow$ fit to experimental data

Hierarchy of nuclear force



M. Piarulli and I. Tews, Front. Phys. **7**, 245 (2019)

Regularization scheme and cutoff function

$$\mathcal{L}_{\text{ChEFT}} \implies V$$

Divergent terms appear for

- high momentum
- short distances

Regularization of $V \longrightarrow$ **cutoff functions**

- $f(p', p; \Lambda)$ or $f(r', r; R) \implies$ **non-local** $V \to p$-space
- $f(p' - p; \Lambda)$ or $f(r; R) \implies$ **local** $V \to r$-space [better with Coulomb]
- $f(p' - p; \Lambda)$ for π-exchange and $f(p', p; \Lambda)$ for contact terms $\implies$ **semi-local** $V \to p$-space

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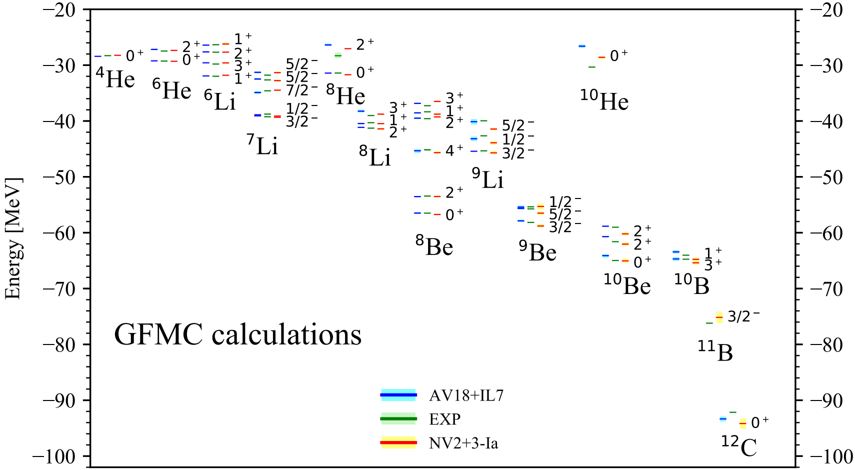
Potentials

Name	Space	Order(s)	Locality	Δ	max E_{LAB}	Λ or (R_L, R_S)
EMN450	p	LO – N^{4}LO	non-local	-less	300 MeV	450 MeV
EMN500	p	LO – N^{4}LO	non-local	-less	300 MeV	500 MeV
EMN550	p	LO – N^{4}LO	non-local	-less	300 MeV	550 MeV
NVIa	r	N^{3}LO	local	-full	125 MeV	$(1.2, 0.8)$ fm
NVIb	r	N^{3}LO	local	-full	125 MeV	$(1.0, 0.7)$ fm
NVIIa	r	N^{3}LO	local	-full	200 MeV	$(1.2, 0.8)$ fm
NVIIb	r	N^{3}LO	local	-full	200 MeV	$(1.0, 0.7)$ fm

[EMN] D. R. Entem, R. Machleidt, and Y. Nosyk, Phys. Rev. C **96**, 024004 (2017)
[NV] M. Piarulli et al., Phys. Rev. C **91**, 024003 (2015)

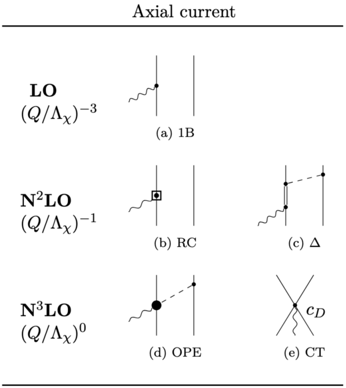


Same degree of success/accuracy as the phenomenological approach!

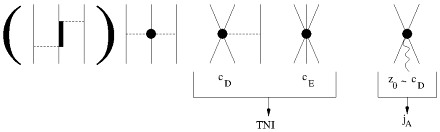
M. Piarulli *et al.*, Phys. Rev. Lett. **120**, 052503 (2018)

Electroweak current in ChEFT

Adding **electroweak field** as DOF



- Similar expansion for the electromagnetic current
- Interplay interaction-current in ChEFT



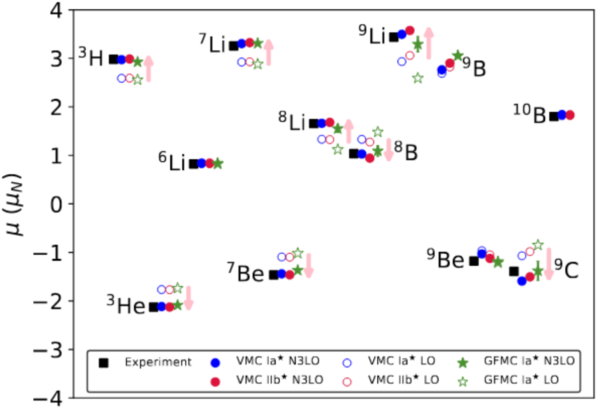
- **LECs fitted to experimental data**
  - **5 LECs** in $j_\gamma \to \mu(A=2,3)$, deuteron $G_M(q^2)$ and $d(e,e')pn$ at threshold
  - z_0-**LEC** in $j_A \to B(^3\mathrm{H})$ & $^3\mathrm{H}$ β-decay half-life

$$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

A. Gnech and R. Schiavilla, Phys. Rev. C **106**, 044001 (2022)

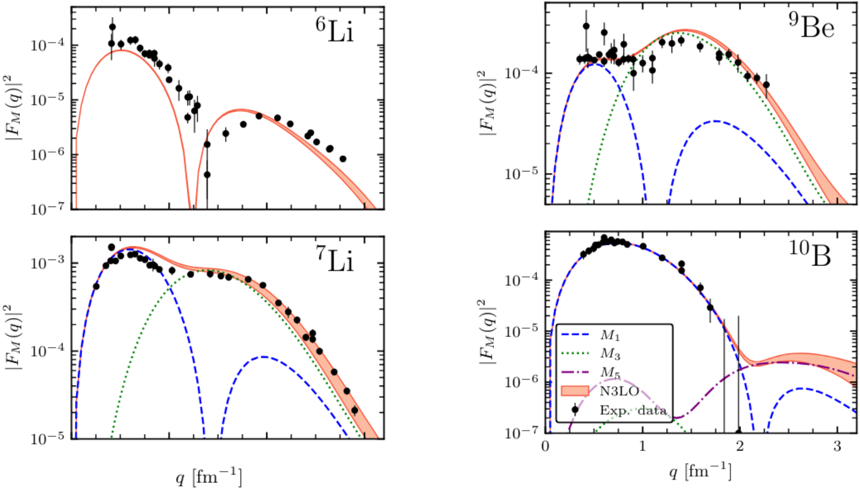
A. Gnech *et al.*, Phys. Rev. C **109**, 035502 (2024)

Magnetic structure of light nuclei: magnetic moments



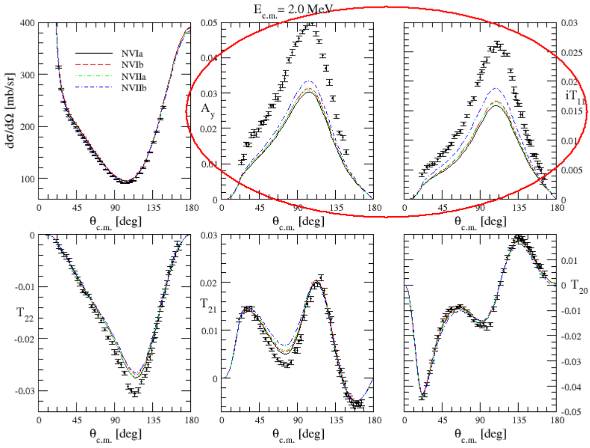
G. Chambers-Wall *et al.*, Phys. Rev. Lett. **133**, 212501 (2024)

Magnetic structure of light nuclei: magnetic form factors



G. Chambers-Wall *et al.*, Phys. Rev. Lett. **133**, 212501 (2024)

Not everything works ... $p + d \to p + d$ elastic scattering



$\longrightarrow$ $\boxed{A_y\text{-puzzle}}$ or iT_{11}-puzzle

$\vec{p} + d \to \vec{p} + d$

$$A_y \propto \frac{\sigma_p(\uparrow) - \sigma_p(\downarrow)}{\sigma_p(\uparrow) + \sigma_p(\downarrow)}$$

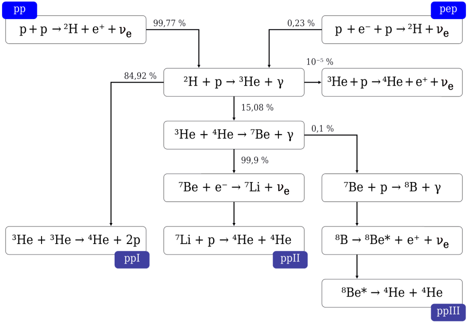
$\vec{d} + p \to \vec{d} + p$

$$\mathrm{i}\,T_{11} \propto \frac{\sigma_d(\uparrow) - \sigma_d(\downarrow)}{\sigma_d(\uparrow) + \sigma_d(\downarrow)}$$

SELECTED RESULTS

for **NUCLEAR REACTIONS of ASTROPHYSICAL INTEREST**

The $p + p \to d + e^+ + \nu_e$ reaction (MS thesis of V. Barlucchi)



- first reaction of the pp-chain $\to$ solar-ν fluxes
- **suppressed** by
  - weak interaction
  - Coulomb barrier

Low energy ($E \sim 6$ keV) $\Longrightarrow$ **quantum tunnelling** $\longrightarrow \sigma(E) \propto P_G(E) = e^{-\pi\alpha\sqrt{m_p/E}}$

S-**factor**

- isolate nuclear physics
- varies slowly at low energies

$$\begin{aligned} S(E) &= E\,\sigma(E)\,P_G^{-1}(E) \\ &\simeq S(0) + S'(0)E + \frac{1}{2}S''(0)E^2 + \frac{1}{6}S'''(0)E^3 \end{aligned}$$

Expansion parameters - fixed current order

$S(E)$ calculated in the $E = 3 - 30$ keV range $\longrightarrow$ Taylor expansion to get $S(0), S'(0)$, etc.

[$\boldsymbol{j}^A$ fixed at N^{3}LO]

Potential	$S(0)$ [10^{-23} MeV fm^2]	$S'(0)/S(0)$ [MeV^{-1}]	$S''(0)/S(0)$ [MeV^{-2}]	$S'''(0)/S(0)$ [MeV^{-3}]
EMN450 N^{3}LO	4.090	10.59	347.2	-6917
EMN500 N^{3}LO	4.091	10.59	346.9	-6911
EMN550 N^{3}LO	4.089	10.59	347.0	-6914
NVIa	4.062	10.61	348.9	-7099
NVIb	4.061	10.61	348.7	-7100
NVIIa	4.036	10.61	348.9	-7096
NVIIb	4.030	10.61	348.7	-7095

To be noticed:

- NV **models I** vs. NV **models II**
- **EMN ChEFT non-local** pot. vs. **NV ChEFT local** pot.

$\rightarrow$ differences in the d wave functions

- $S'(0)/S(0)$, $S''(0)/S(0)$ etc $\rightarrow$ model-independent

Theoretical error

Theoretical uncertainties $\longrightarrow$ **truncation chiral expansion** of

- interactions
- currents

S(E) calculated at N^{n}LO

$$S_n(E) = S_{\text{ref}}(E) \sum_{k=0}^{n} c_k(E) \left(\frac{Q(E)}{\Lambda_b} \right)^k$$

- $Q(E) = \frac{(m_p E)^4 + m_\pi^8}{(m_p E)^{7/2} + m_\pi^7}$
- $\Lambda_b = 600$ MeV

Truncation error $\boldsymbol{\sigma_n(E)}$ $\simeq$ contribution of order $n+1$

$$\sigma_n(E) = \max \left[\left\{ |S_k(E) - S_{k-1}(E)| \left(\frac{Q(E)}{\Lambda_b} \right)^{n-k+1} \right\}_{k=0,\ldots,n} \right]$$

J. A. Melendez *et al.*, Phys. Rev. C **100**, 044001 (2019)

Truncation error - interaction

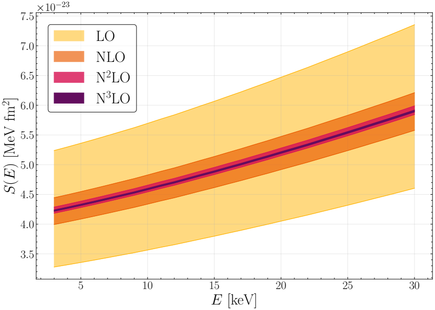
Current fixed at

- N^2LO for EMN LO, NLO
- N^3LO for EMN N^2LO, N^3LO and NV

EMN

Potential	$\sigma_0^{\rm Int}(0)$	$\sigma_1^{\rm Int}(0)$	$\sigma_2^{\rm Int}(0)$	$\sigma_3^{\rm Int}(0)$
EMN450	0.940	0.216	0.050	0.011
EMN500	0.944	0.218	0.051	0.011
EMN550	0.955	0.220	0.051	0.012

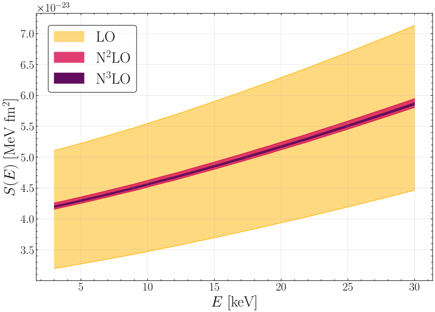
$\sigma_n^{\rm Int}(0)$ in unit of 10^{-23} MeV fm^2



NV

$$\sigma_{\rm NV}^{\rm Int}(E) = \frac{S_{\rm NVIa}(E) - S_{\rm NVIIb}(E)}{2} \quad \longrightarrow \quad \sigma_{\rm NV}^{\rm Int}(0) = 0.016 \times 10^{-23}\ \text{MeV fm}^2$$

Truncation error - current



Interaction fixed at

- N^3LO in both EMN and NV

Potential	$\sigma_0^{\rm Cur}(0)$	$\sigma_2^{\rm Cur}(0)$	$\sigma_3^{\rm Cur}(0)$
EMN450	0.928	0.049	0.013
EMN500	0.931	0.049	0.011
EMN550	0.933	0.049	0.011
NVIa	0.924	0.049	0.011
NVIb	0.923	0.049	0.011
NVIIa	0.918	0.049	0.011
NVIIb	0.917	0.049	0.011

$\sigma_n^{\rm Cur}(0)$ in unit of 10^{-23} MeV fm^2

Final results

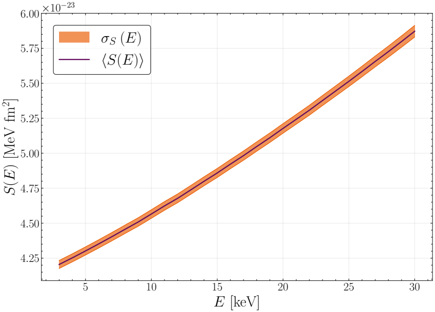
A. Gnech *et al.*, Phys. Rev. C **109**, 035502 (2024): procedure used for $\mu^- + d \to n + n + \nu_\mu$

$$\langle S(E)\rangle = \sum_i S_i(E)\, P_i$$

$$P_i = \begin{cases} \frac{1}{6} & \text{for EMN potentials} \\ \frac{1}{8} & \text{for NV potentials} \end{cases}$$

$$\sigma_S^2(E) = \langle S^2(E)\rangle - \langle S(E)\rangle^2 + \sum_i \sigma_i^2(E)\, P_i$$

$$\sigma_i(E) = \sigma_i^{\rm Int}(E) + \sigma_i^{\rm Cur}(E)$$

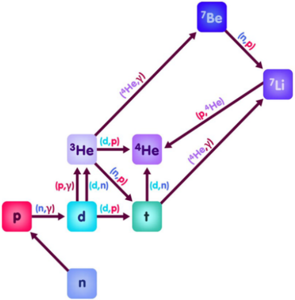


$$\boxed{S_{\rm EMN+NV}(0) = 4.069\,(1 \pm \underset{\rm Trunc.}{0.007}) \times 10^{-23}\ \text{MeV fm}^2}$$

To be compared with: Solar Fusion III
[B. Acharya *et al.*, arXiv: 2405.06470 (2024) to be published in Rev. Mod. Phys.]

$$S(0) = 4.090\,(1 \pm \underset{\rm Trunc.}{0.005} \pm \underset{\rm Syst.}{0.010}) \times 10^{-23}\ \text{MeV fm}^2$$! no local ChEFT potential

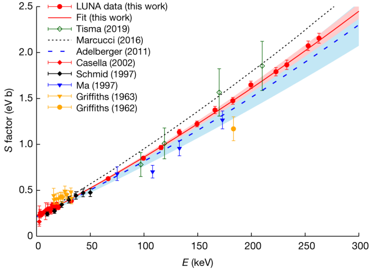
BBN and d abundance: the ^{2}H$(p,\gamma)^3$He reaction



1) $n \rightarrow {}^1H + e^- + \bar{\nu}$
2) $^1H + n \rightarrow {}^2H + \gamma$
3) $^2H + {}^1H \rightarrow {}^3He + \gamma$
4) $^2H + {}^2H \rightarrow {}^3He + n$
5) $^2H + {}^2H \rightarrow {}^3H + {}^1H$
6) $^2H + {}^3H \rightarrow {}^4He + n$
7) $^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) $^3He + n \rightarrow {}^3H + {}^1H$
9) $^3He + {}^2H \rightarrow {}^4He + {}^1H$
10) $^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) $^7Li + {}^1H \rightarrow {}^4He + {}^4He$
12) $^7Be + n \rightarrow {}^7Li + {}^1H$
13) $^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) $^6Li + {}^1H \rightarrow {}^3He + {}^3He$

LUNA data

V. Mossa *et al.*, Nature **587**, 210 (2020)



$$10^5 (\mathrm{D/H})_{\mathrm{BBN}} = 2.52 \pm 0.03 \pm 0.06$$

vs.

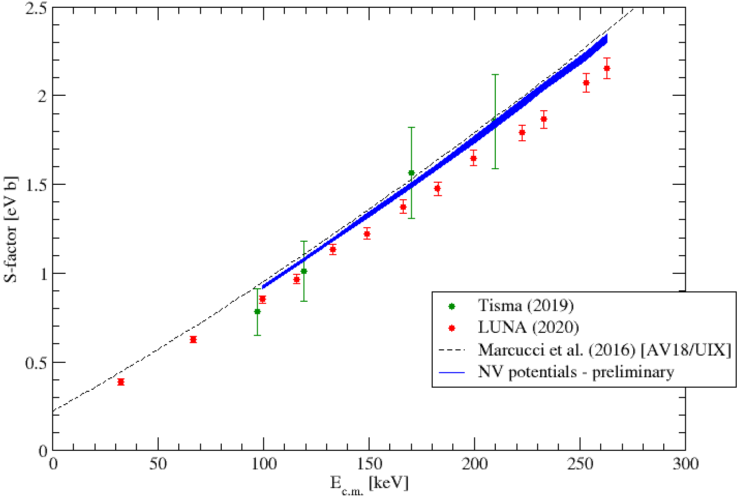
$$10^5 (\mathrm{D/H})_{\mathrm{exp}} = 2.527 \pm 0.030$$

R.J. Cooke *et al.*, Astrophys. J. **885**, 102 (2018)

- - - - - Phenomenological approach (AV18/UIX) $\longrightarrow$ what is the theoretical uncertainty?

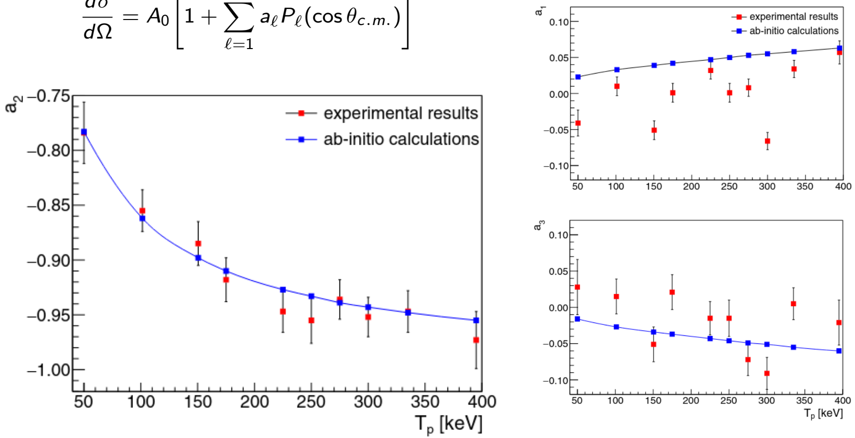
$\Rightarrow$ ChEFT [work in progress]

The $^2H(p,\gamma)^3He$ reaction - ChEFT - PRELIMINARY



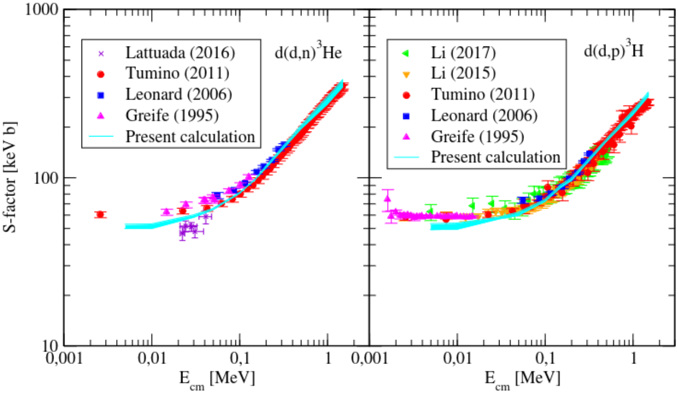
The ^{2}H$(p,\gamma)^3$He reaction - angular distribution

$$\frac{d\sigma}{d\Omega} = A_0\left[1 + \sum_{\ell=1}^{3} a_\ell P_\ell(\cos\theta_{c.m.})\right]$$



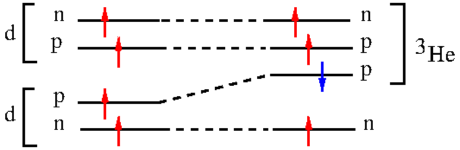
K. Stöckel *et al.*, Phys. Rev. C **110**, L032801 (2024)

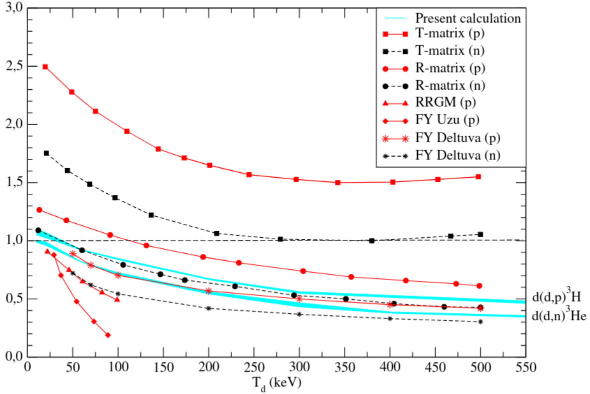
BBN and d abundance: $d(d,p)^3\mathrm{H}$ and $d(d,n)^3\mathrm{He}$



M. Viviani *et al.*, Phys. Rev. Lett. **130**, 122501 (2023)

$\vec{d}(\vec{d},n)^3\mathrm{He}$ & $\vec{d}(\vec{d},p)^3\mathrm{H}$ suppressed in S-wave





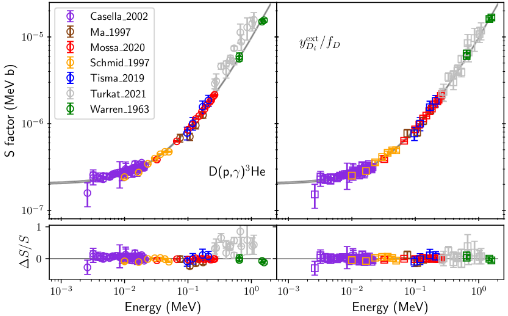
$\Rightarrow$ “neutron lean” reactors

What have we learned:

- Lot of reactions at reach $(A = 2, 3, 4 \cdots)$
- In general "good" *ab-initio* predictions
- Predictions accompanied by theoretical error estimate
- Some "puzzles" still there
    1. $p + d \to {}^3\mathrm{He} + \gamma$
    2. A_y-puzzle in $p + d$ elastic scattering

Puzzles: 1) $p + d \to {}^3\mathrm{He} + \gamma$

- calculation to be performed with the non-local ChEFT potentials (EMN)
- calculation to be extended to higher energy values

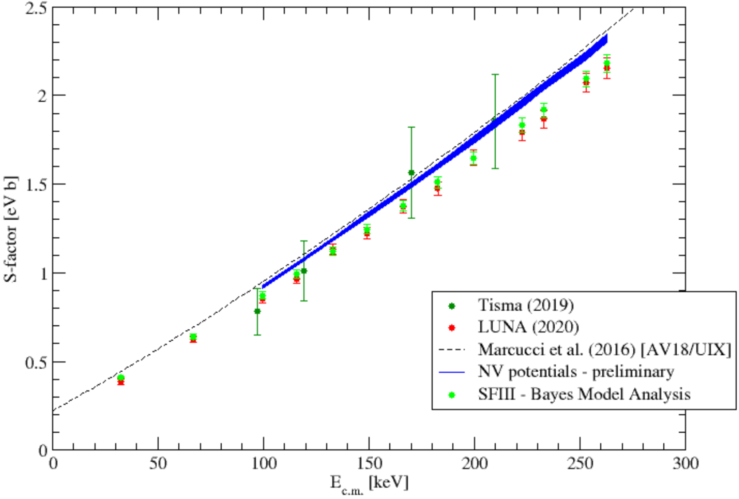


	E = 262.9 keV	222.8 keV	166.1 keV	99.5 keV
LUNA[1]	2.156(58)	1.791(45)	1.375(36)	0.850(22)
Bayes Model Analysis[2]	2.181(45)(3)	1.834(38)(2)	1.376(28)(1)	0.873(18)(4)
NV-ChEFT	2.32(3)	1.96(3)	1.46(2)	0.92(2)

[1] V. Mossa *et al.*, Nature **587**, 210 (2020)

[2] A. Walker-Loud, `https://github.com/nrp-g/leaner`, Solar Fusion III, arXiv: 2405.06470 (2024)

PRELIMINARY



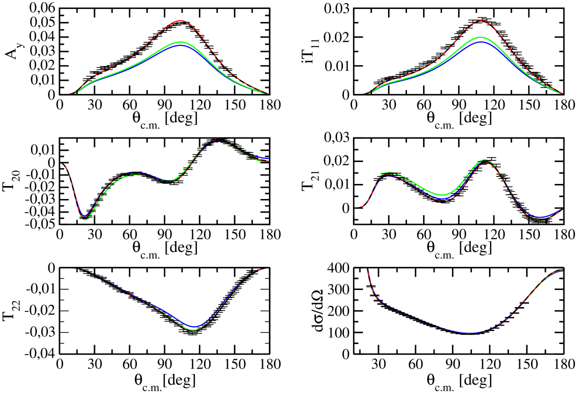
N3LO $2N$ contact interactions

E. Filandri *et al.*, Few-Body Syst. **65**, 57 (2024)

$$V_{2N}^{\rm N3LO} = \sum_{i=1}^{15} D_i \mathcal{O}_i(\boldsymbol{k}, \boldsymbol{Q}) + iD_{16}\, \boldsymbol{k}\cdot\boldsymbol{Q}\, \boldsymbol{Q}\times\boldsymbol{P}\cdot(\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2}) + D_{17}\, \boldsymbol{k}\cdot\boldsymbol{Q}\,(\boldsymbol{k}\times\boldsymbol{P})\cdot(\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2})$$

$$\boldsymbol{k} = \boldsymbol{p}' - \boldsymbol{p} \qquad \boldsymbol{Q} = \frac{\boldsymbol{p}'+\boldsymbol{p}}{2} \qquad \boldsymbol{P} = \boldsymbol{p}_1 + \boldsymbol{p}_2$$

The $\boldsymbol{P} = 0$ in 2N,
but $\boldsymbol{P} \neq 0$ in 3N
$\Rightarrow$ Unitary-transformation
$\rightarrow V_{3N}$



Conclusions and outlook

Conclusions

Ab-initio approaches are a powerfull tool for

- providing **insights** on the nature of **nuclear interactions** and nuclear systems more in general;
- providing **predictions** together with a **robust estimate of theoretical uncertainties**.

Outlook: many ideas

- Move to $A > 3, 4$
- Move to hypernuclear systems
  - ChEFT for hypernuclear interactions and currents
  - *ab-initio* approaches for bound and scattering hypernuclear states

Collaborators

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- **V. Barlucchi** (MS, Pisa Univ. $\rightarrow$ PhD Mainz Univ. $+$ Pisa Univ.)
- **E. Proietti** (PhD, Pisa Univ.)
- **M. Sagina** (MS $\rightarrow$ PhD, Pisa Univ.)
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- L. Girlanda (Salento Univ.)
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Thank you for your attention!

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