Spin-tensor decomposition of nuclear forces from chiral Effective Field Theory

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Contents

Motivation: Nuclear Forces

One of the most important thing in nuclear physics is to determine the interaction between nucleons. In perticular, the importance of three-body force is not only for nuclear physics, but for astrophysical processes.

chiral effective field theory

many-body forces are naturally derived as the orders of ‘perturbation expansion’ be higher.
Chiral EFT is thought to be a candidate to discribe nuclear forces in a systematic and consistent way.

In this presentation, I will show some features of nuclear forces from chiral EFT obtained by quantitative analysis of its potentials.

What is chiral EFT **?**

Overview of Effective Field Theory

S.Weinberg, "Phenomenological Lagrangians". Physica A 96 (1-2): 327-340

"... if one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order in perturbation theory, the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry principles."

Integrating out heavy degrees of freedom and regarding only "light particles" as effective degrees of freedom, we can write down effective Lagrangians consistent with symmetry of underlying theory and construct effective theory.

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- symmetry of underlying theory(QCD) = chiral symmetry
- light particles=nucleons and pions → chiral Effective Field Theory

Chiral symmetry

Chiral symmetry breaking

Chiral symmetry is the approximate symmetry of QCD.
It is spontaneously broken. $SU(2)_L \times SU(2)_R \to SU(2)_V$

→ generation of hadron masses.
→ pions emarge as corresponding Nambu-Goldstone bosons
→ interactions between NG bosons (low-energy theorem)

chiral symmetry is also explicitly broken due to the existence of nonvanising masses of quarks

→ pions aquire the finite masses.

Chiral expansion

At low energy region, coupling constant becomes large and one can no longer rely on perturbation theory.
We want some alternative expantion parameter to describe low-energy phenomena.

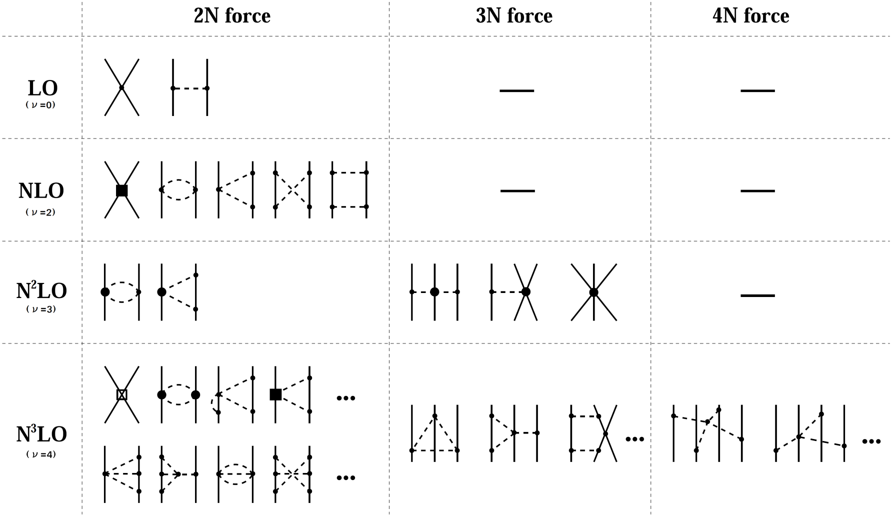
$$\left(\frac{Q}{\Lambda_\chi}\right)^\nu$$

Λ_χ : hard scale (chiral symmetry breaking scale) $\sim$ 1 GeV
Q : soft scale (nucleon external momentum or pion mass)
ν : power

ν is determined by dimension analysis, powor counting.

$\rightarrow$ classifying the contributions of irreducible diagrams by ν

The hierarchy of Nuclear Forces



Ref. E.Epelbaum, arXiv:1001.3229 [nucl-th] (2010)

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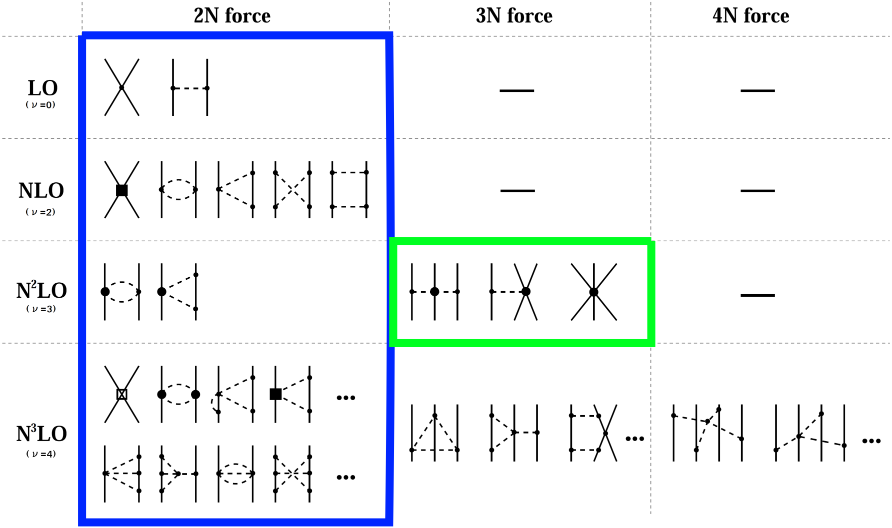

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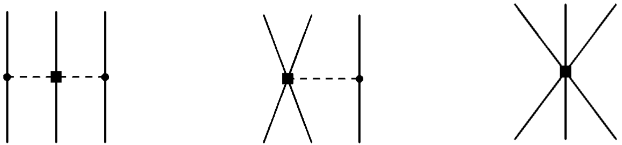
chiral potentials e.g. 3NF in NNLO



(a) TPE (b) OPE (c) Contact

$$V^{3NF}_{TPE} = \frac{1}{2}\left(\frac{g_A}{2f_\pi}\right)^2 \sum_{i\neq j\neq k} \frac{(\boldsymbol{\sigma}_i\cdot\mathbf{q}_i)(\boldsymbol{\sigma}_j\cdot\mathbf{q}_j)}{(q_i^2+m_\pi^2)(q_j^2+m_\pi^2)}\tau_i^\alpha\tau_j^\beta$$

$$\times\left\{\delta^{\alpha\beta}\left[-\frac{4c_1 m_\pi^2}{f_\pi^2}+\frac{2c_3}{f_\pi^2}\mathbf{q}_i\cdot\mathbf{q}_j\right]+\sum_\gamma \frac{c_4}{f_\pi^2}\epsilon^{\alpha\beta\gamma}\tau_k^\gamma\boldsymbol{\sigma}_k\cdot(\mathbf{q}_i\times\mathbf{q}_j)\right\}$$

$$V^{3NF}_{OPE} = -\frac{g_A}{8f_\pi^2}\frac{c_D}{f_\pi^2\Lambda_\chi}\sum_{i\neq j\neq k}\frac{(\boldsymbol{\sigma}_j\cdot\mathbf{q}_j)(\boldsymbol{\sigma}_i\cdot\mathbf{q}_j)}{q_j^2+m_\pi^2}(\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j)$$

$$V^{3NF}_{cont} = \frac{c_E}{2f_\pi^4\Lambda_\chi}\sum_{j\neq k}(\boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k) = \frac{c_E}{f_\pi^4\Lambda_\chi}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2+\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3+\boldsymbol{\tau}_3\cdot\boldsymbol{\tau}_1)$$

Shell-model interaction

We expand these potentials by two-body shell model besis
$|n_i j_i(l_i s_i); n_j j_j(l_j s_j)\rangle$
For three-body forces...transform into effective two-body forces.

$$\langle \mathbf{k}_1'\sigma_1'\tau_1', \mathbf{k}_2'\sigma_2'\tau_2' | V_{12(3)} | \mathbf{k}_1\sigma_1\tau_1, \mathbf{k}_2\sigma_2\tau_2\rangle$$
$$\equiv \sum_{\mathbf{k}_3\sigma_3\tau_3} \langle \mathbf{k}_1'\sigma_1'\tau_1', \mathbf{k}_2'\sigma_2'\tau_2', \mathbf{k}_3'\sigma_3'\tau_3' | V_{123} | \mathbf{k}_1\sigma_1\tau_1, \mathbf{k}_2\sigma_2\tau_2, \mathbf{k}_3\sigma_3\tau_3\rangle$$

"summing over third nucleon in Fermi sea of nuclear matter"
Ref. M. Kohno, Phys. Rev. C 88, 064005(2013)

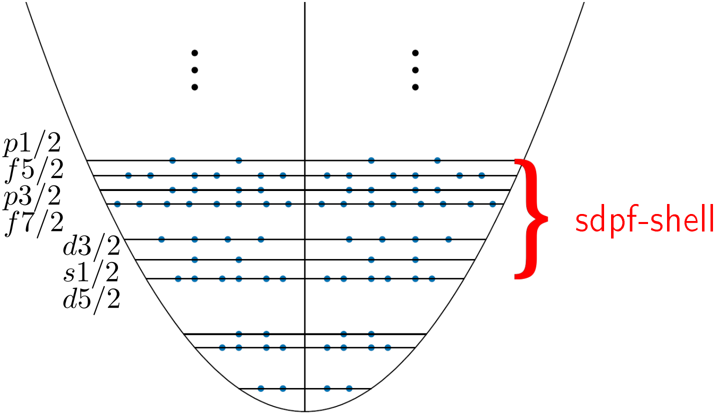
In matter calculation, $c_D \sim 4c_E$ setting is known to give reasonable saturation curve.($c_D = -4.381$,$c_E = -1.126$)
Ref. K. Hebeler, *et al.* , Phys. Rev. C 83, 031301(2011)

Spin-tensor decomposition

The form of nuclear potentials are limited to scaler operator composed of rank0, 1, and 2 irreducible tensor operators.
According to Racah algebra, nuclear potentials can be decomposed into ...
p=0 : central, p=1 : spin-orbit(ls), p=2 : tensor (p denotes the rank of ingrediant operators)

$$\langle ABLSJ'T|V_p|CDL'S'J'T\rangle = (-1)^{J'}(2p+1)\begin{Bmatrix} L & S & J' \\ S' & L' & p \end{Bmatrix}$$
$$\times \sum_J (-1)^J (2J+1)\begin{Bmatrix} L & S & J \\ S' & L' & p \end{Bmatrix}\langle ABLSJ'T|V|CDL'S'JT\rangle$$

Ref. M.W. Kirson, Physics Letters B | Vol 45, Iss 2, Pgs 77-170 (1973)



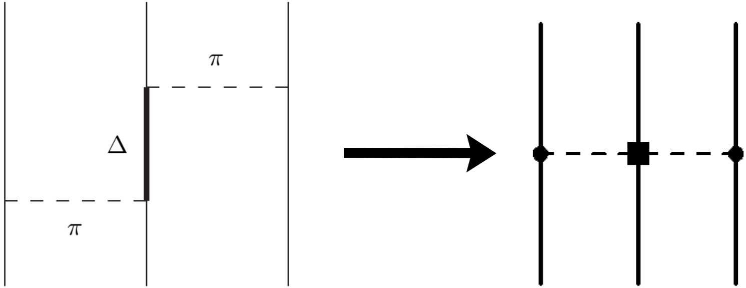
We focus on sdpf-shell ...
And for simplicity, we will look at only monopole components

$$V^T_{j,j'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

This time we use two different chiral EFT interactions
(Epelbaum,Glöckle,Meißner's(EGM) and Entem, Machleidt(EM))

I will show following results for the monopole components.

- How large is **3** NF (to 2NF) **?**
- How large is contribution from each diagrams in **3** NF **?**
- Comperison with conventional Fujita-Miyazawa type **3** NF.



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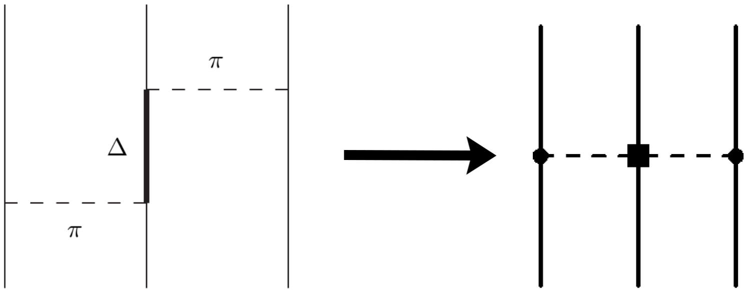
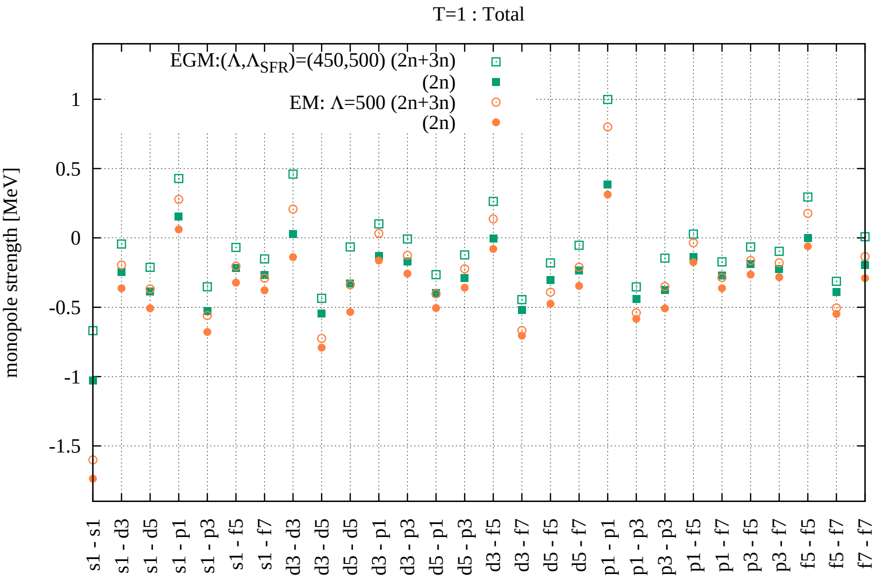


2NF vs 2NF+3NF : total for T=1



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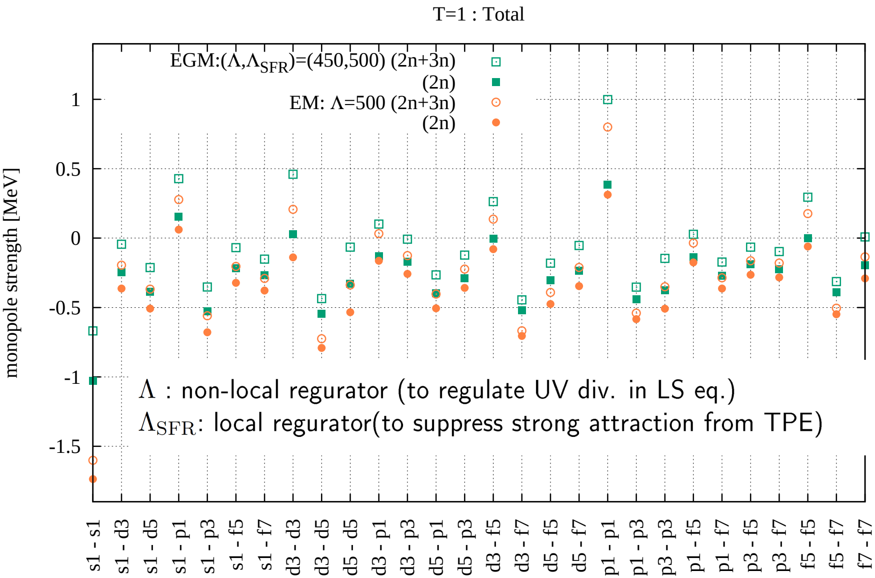
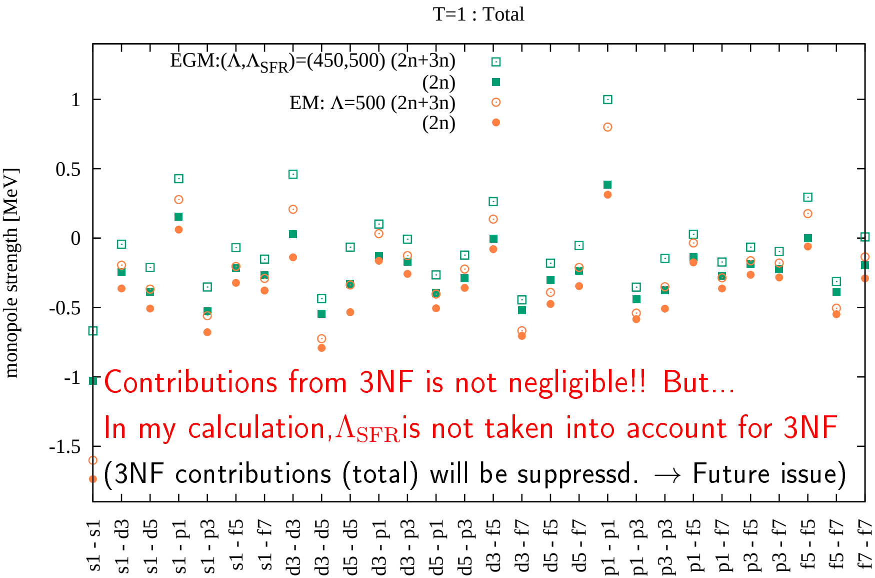


Λ : non-local regurator (to regulate UV div. in LS eq.)

Λ_{SFR}: local regurator(to suppress strong attraction from TPE)

2NF vs 2NF+3NF : total for T=1



Contributions from 3NF is not negligible!! But...

In my calculation, Λ_{SFR} is not taken into account for 3NF

(3NF contributions (total) will be suppressd. → Future issue)

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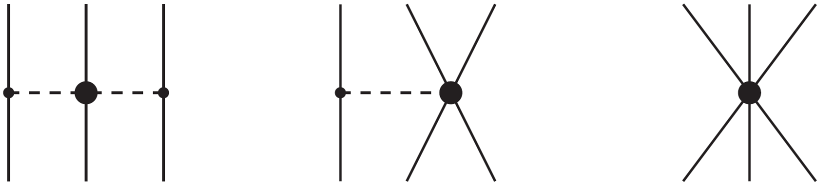
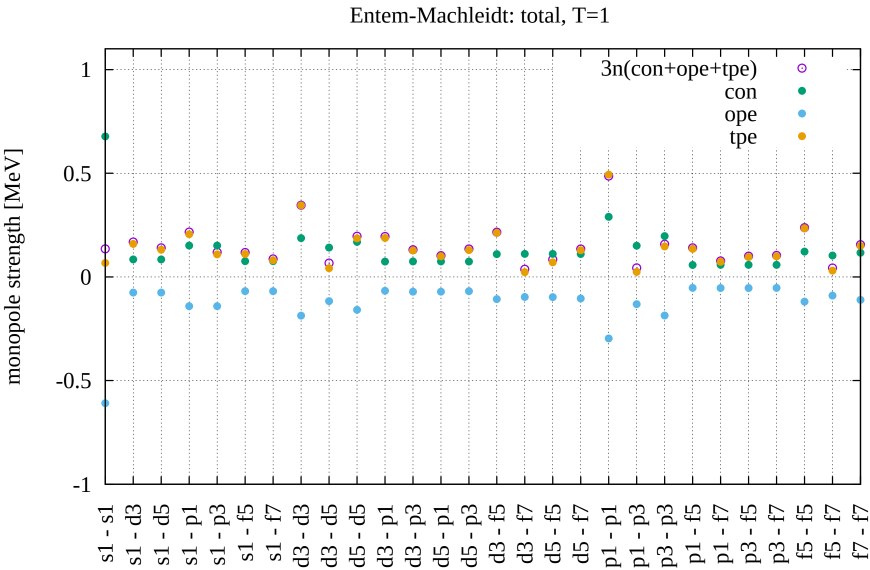


Entem &Machleidt : 3NF components



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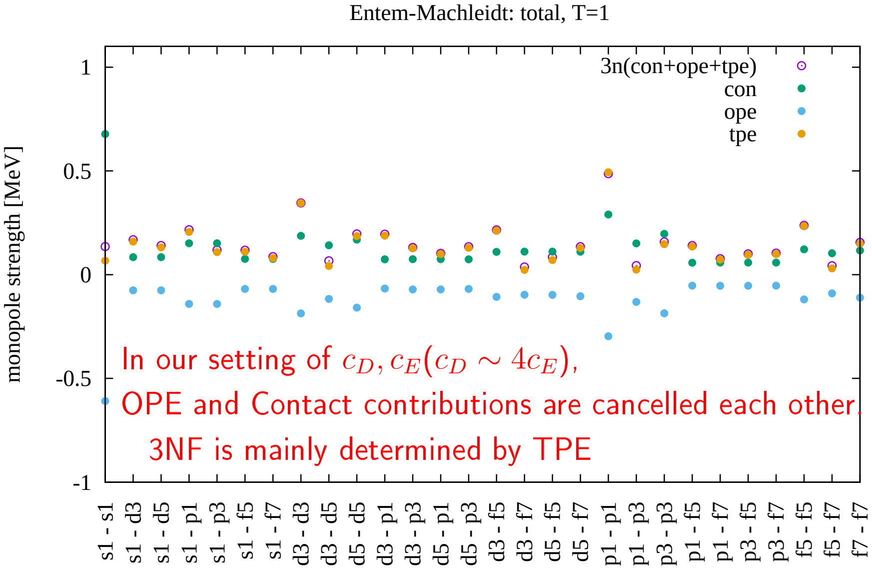
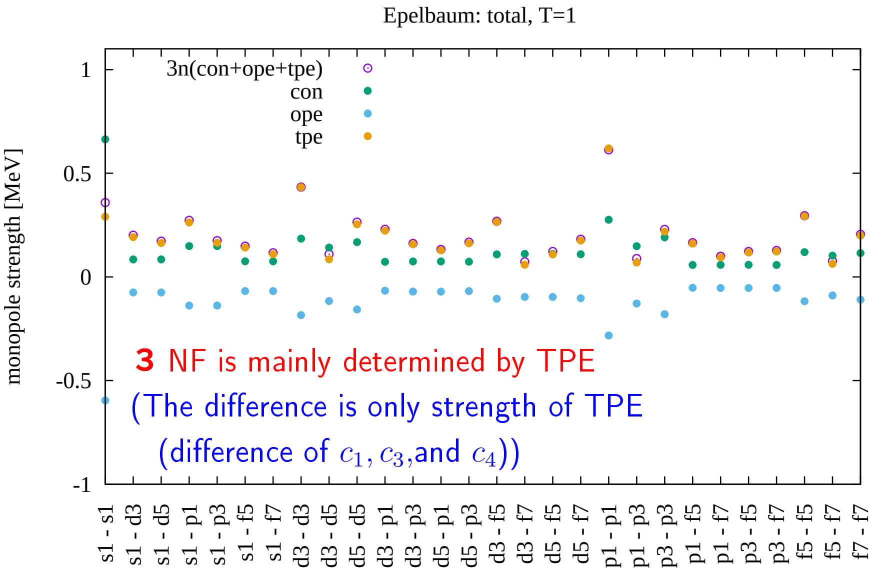


In our setting of $c_D, c_E (c_D \sim 4c_E)$,

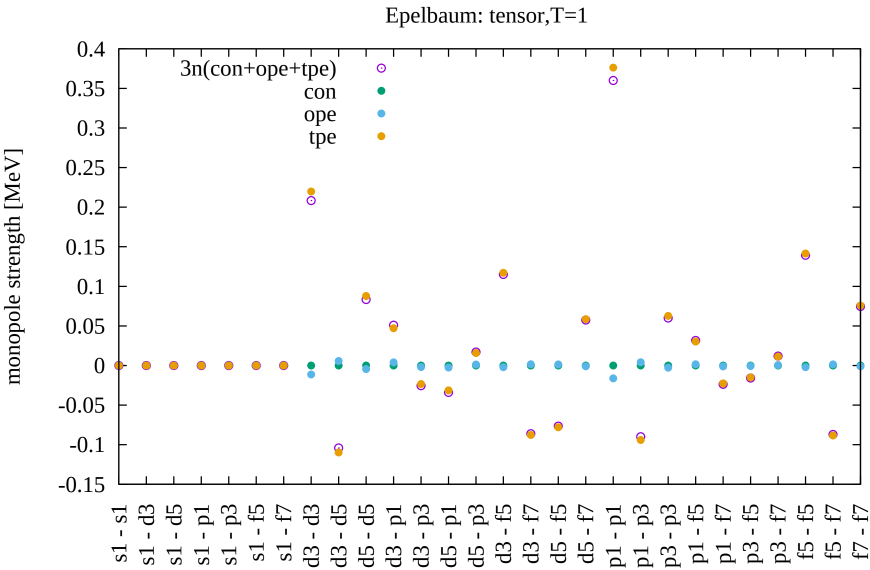
OPE and Contact contributions are cancelled each other.

3NF is mainly determined by TPE

Epelbaum *et al.* : 3NF components



Appendix:Epelbaum *et al.* : 3NF components



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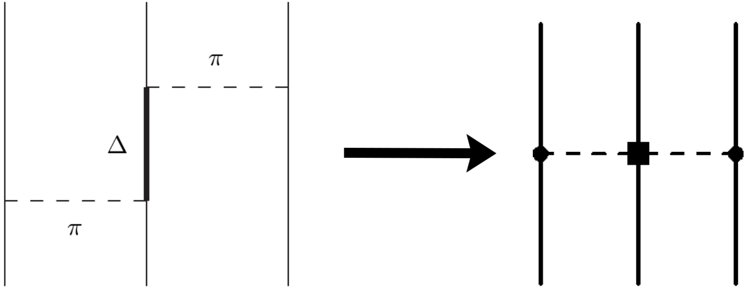
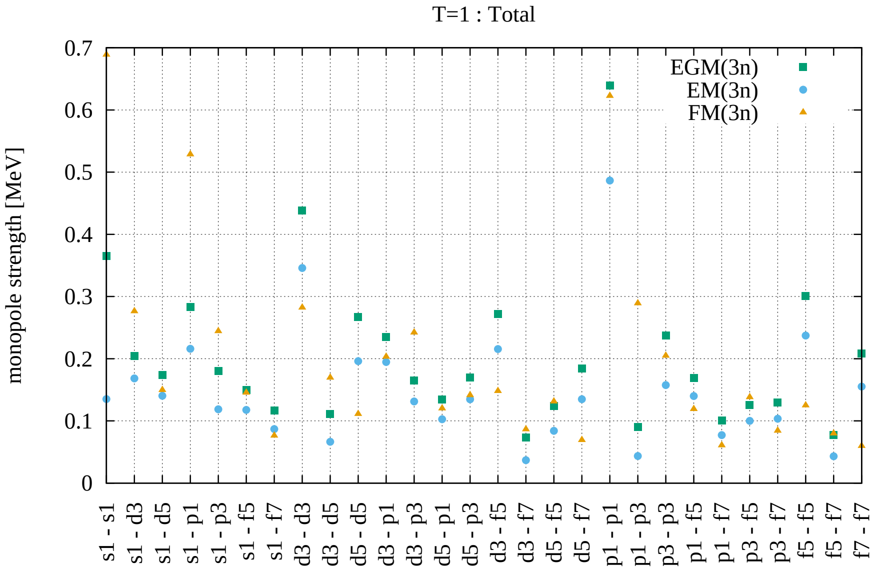
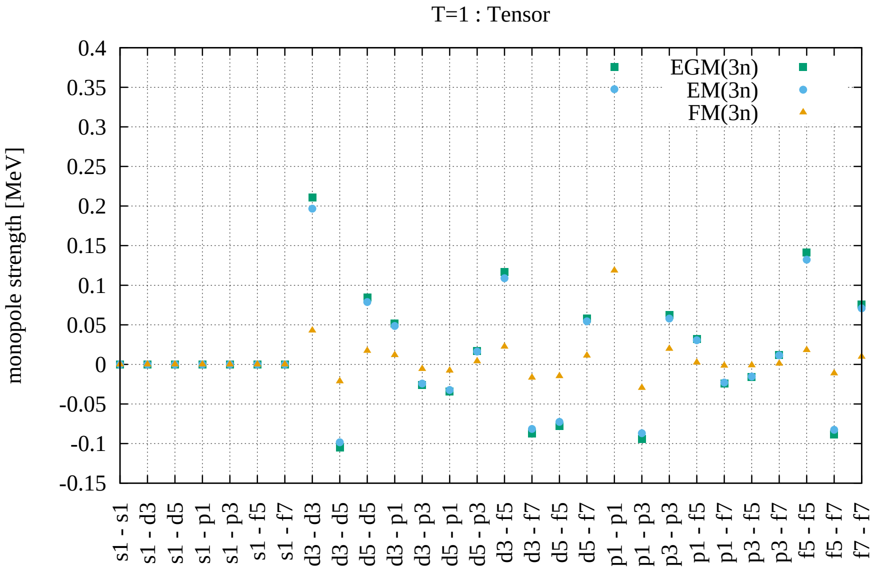


3NFs vs Fujita-Miyazawa 3NF : Total



3NFs vs Fujita-Miyazawa 3NF : Tensor



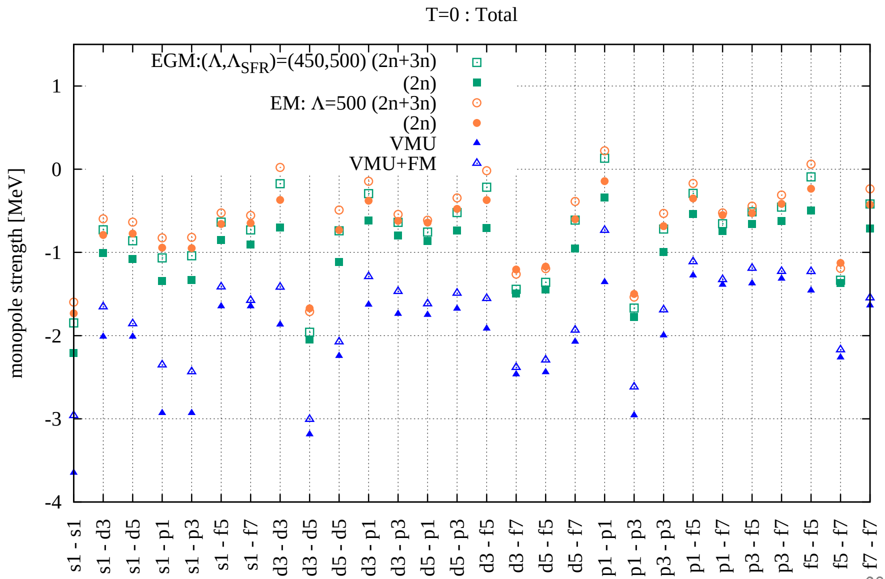
Summary

- 3NF from chiral EFT is not negligible (vs 2NF contribution) note)Λ_{SFR}(local-regulator to suppress TPE contribution)is not taken into account for 3NF)
- Assuming $c_D \sim 4c_E$, 3NF is mainly determined by TPE
- The total tendency of chiral EFT 3NF are similar to FM type 3NF, but the Tensor part from chiral EFT is much larger than FM .

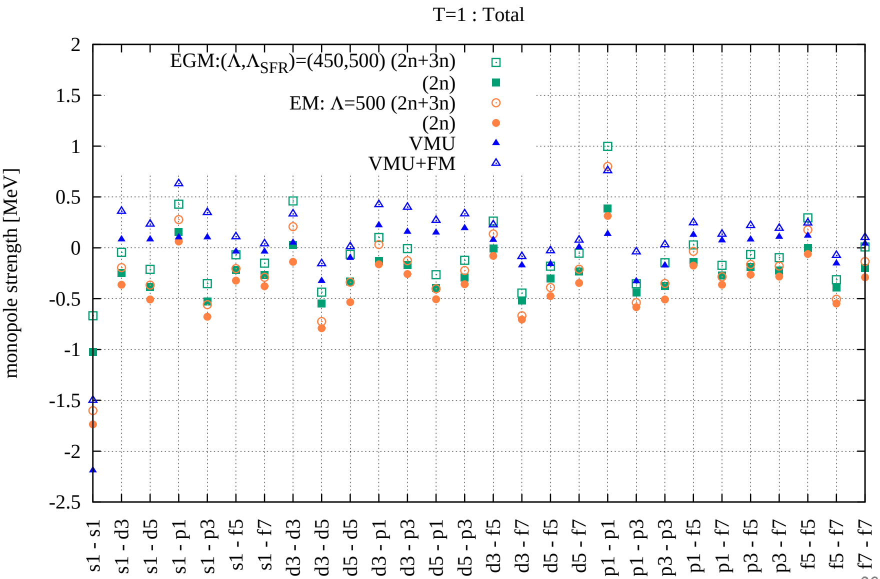
Future Issues

- How about different settings of c_D and c_E ?
- Improvement in the treatment of 3NF (Λ_{SFR}, how to transform effecive 2NF, and so on.)
- Construntion of effective interactions for shell-model calculation and calculation of concrete observables for some specific nuclei.
- whether we can discuss c_D or c_E from some structure calculation ?

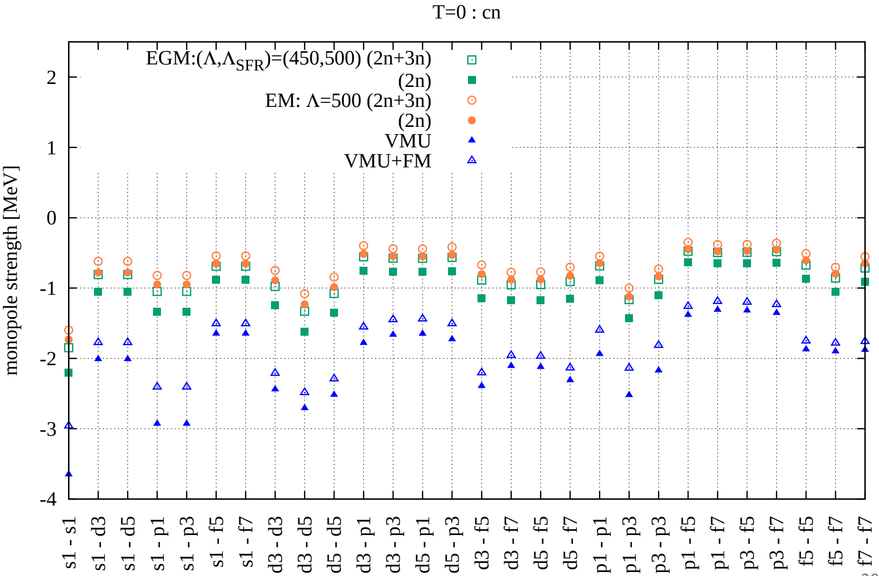
Appendix:chiral EFT vs conventional NF : total : T=0



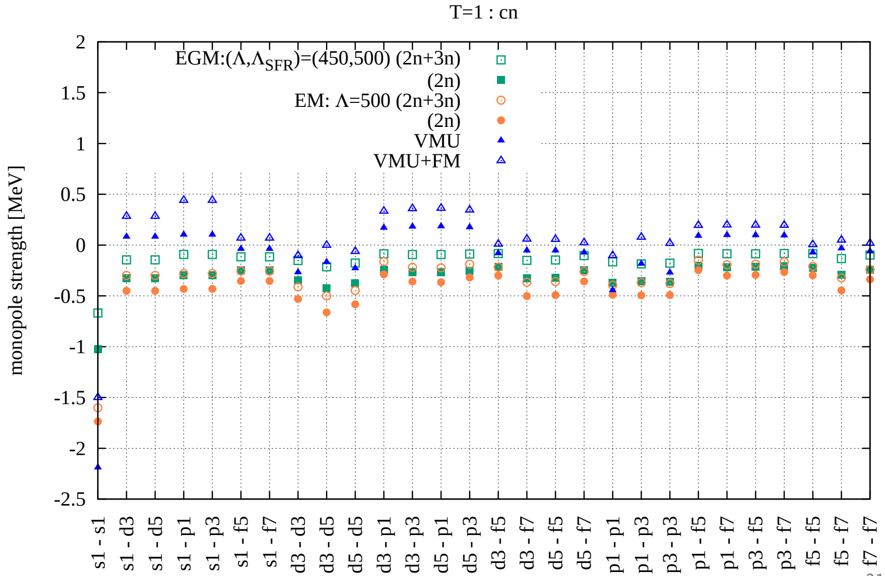
Appendix:chiral EFT vs conventional NF : total : T=1



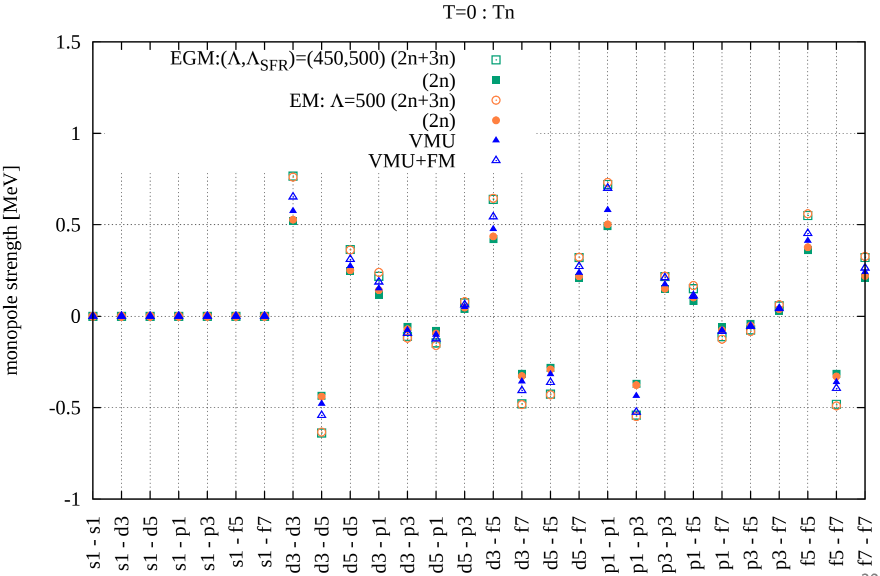
Appendix:chiral EFT vs conventional NF : central : T=0



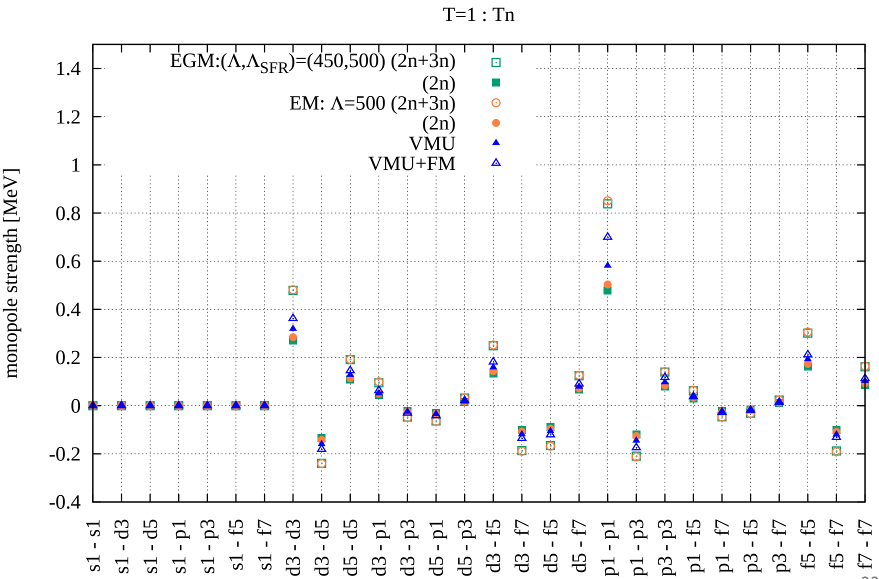
Appendix:chiral EFT vs conventional NF : central : T=1



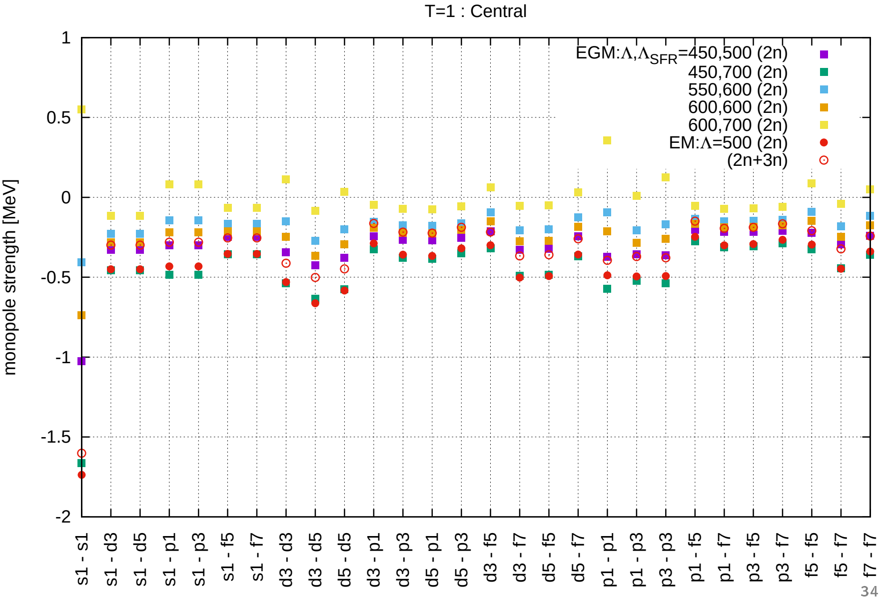
Appendix:chiral EFT vs conventional NF : tensor : T=0



Appendix:chiral EFT vs conventional NF : tensor : T=1



Appendix1:SFR dep.



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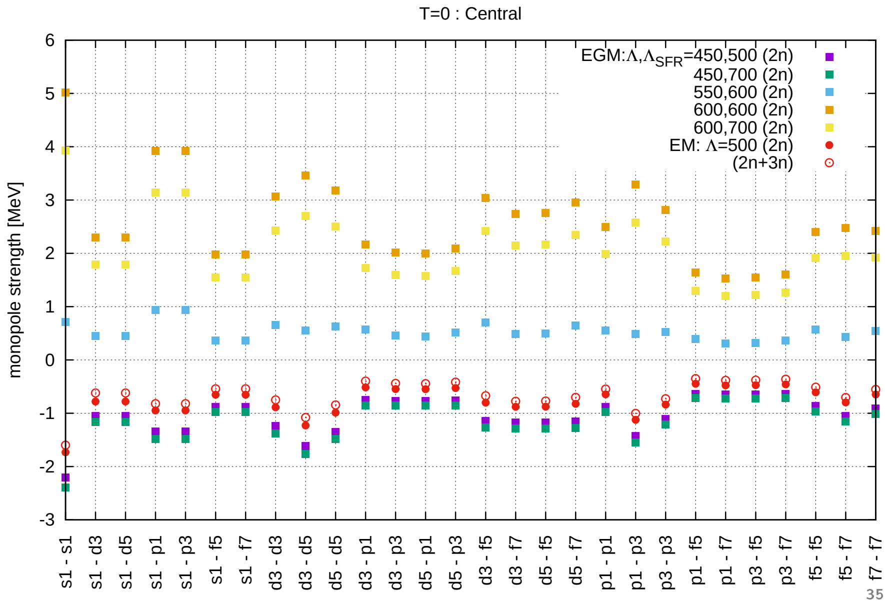

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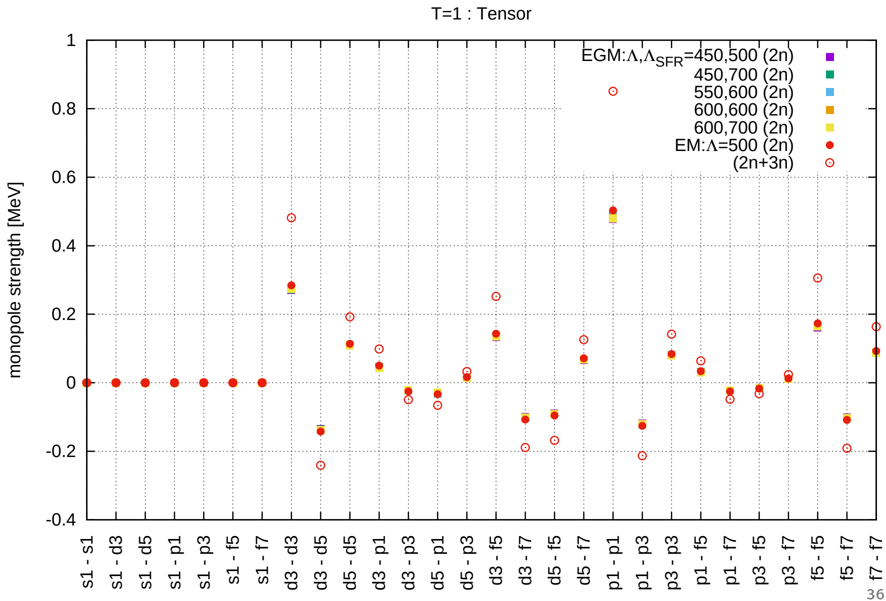

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