Isospin-breaking effects in NN scattering

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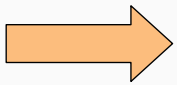
Isospin-breaking (IB)-extended SMS potential

- N^4LO^+ SMS potential achieves χ^2/datum ~ 1
- But isospin-breaking (IB) limited to pion-mass splitting in One-pion-exchange and charge-dependent short-range interactions in $^1S_0$

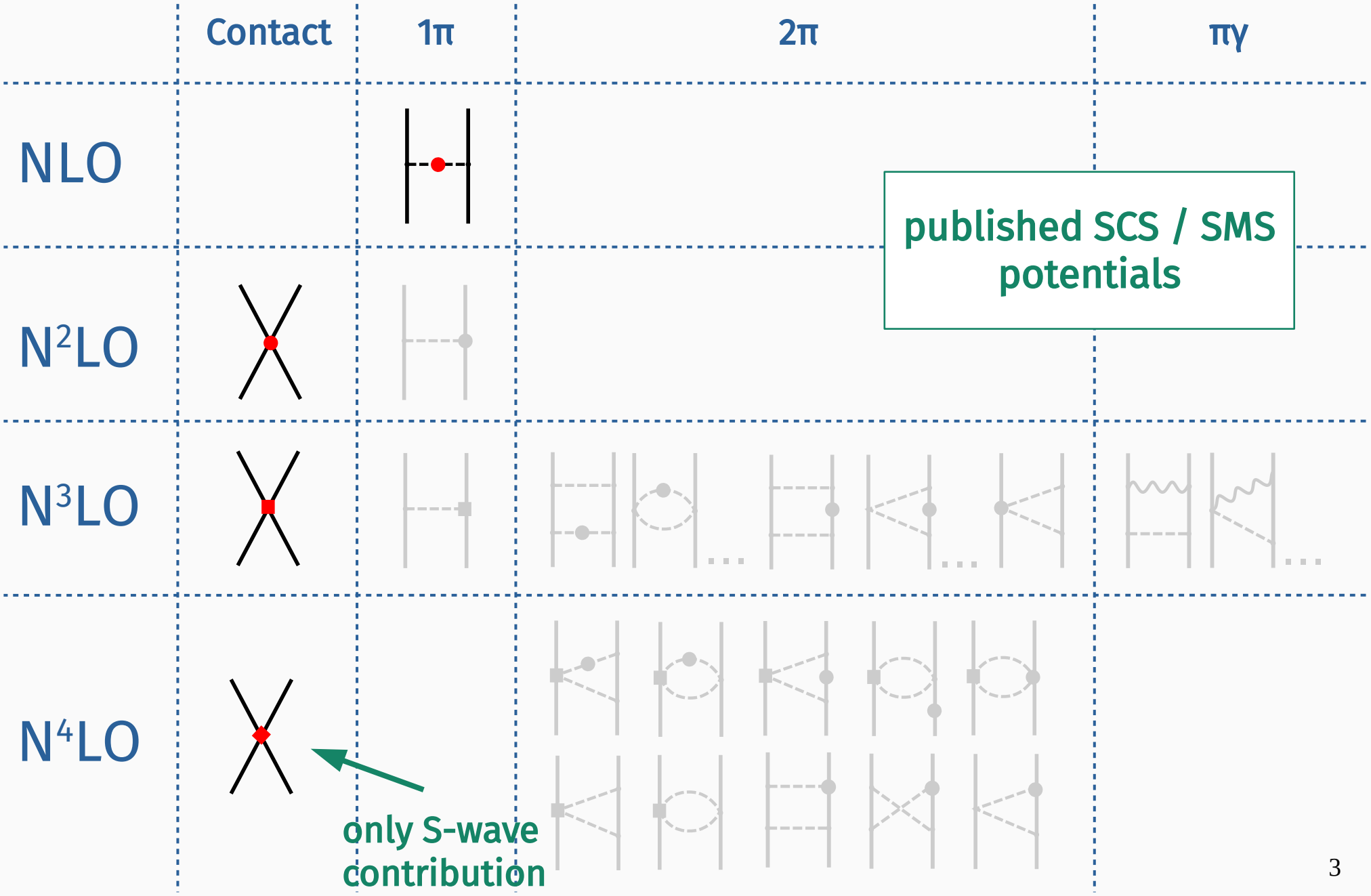
This talk: **Refined 2N SMS interaction with complete isospin-breaking effects up to Q^5**

- Already employed in calculations: Deuteron form factors [Phys. Rev. C 103.024313], charge radii & magnetic moments of light nuclei



see talks by Arseniy & Daniel

Overview of IB contributions [Phys. Rev. C **72**, 044001 (2005)]



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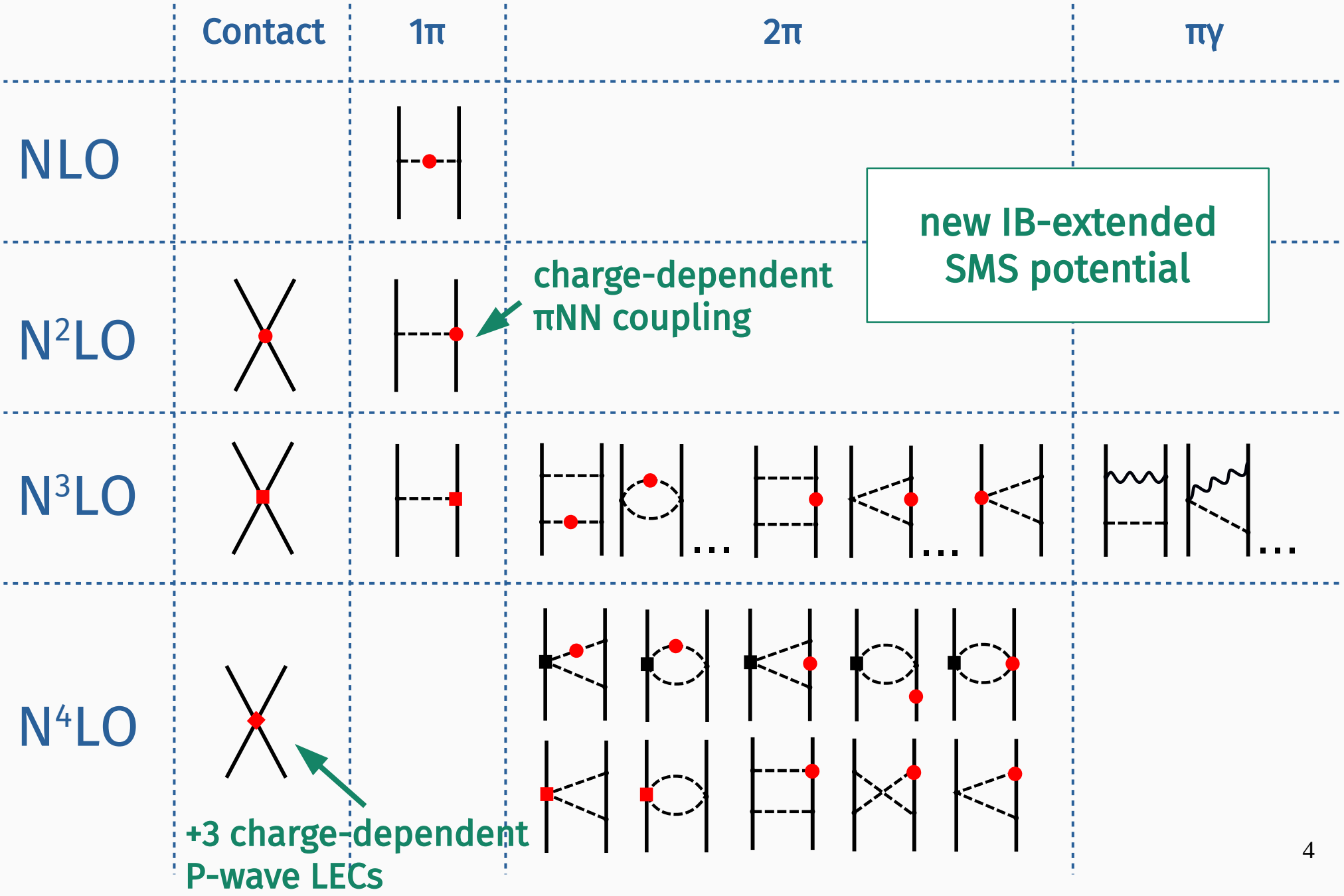
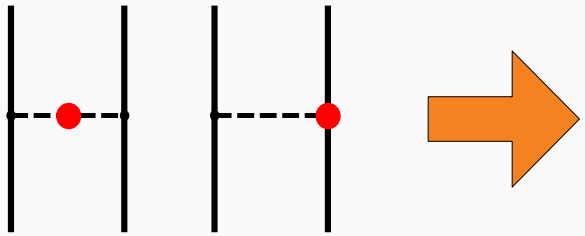


Charge-dependent πNN couplings



General OPE without isospin limit:

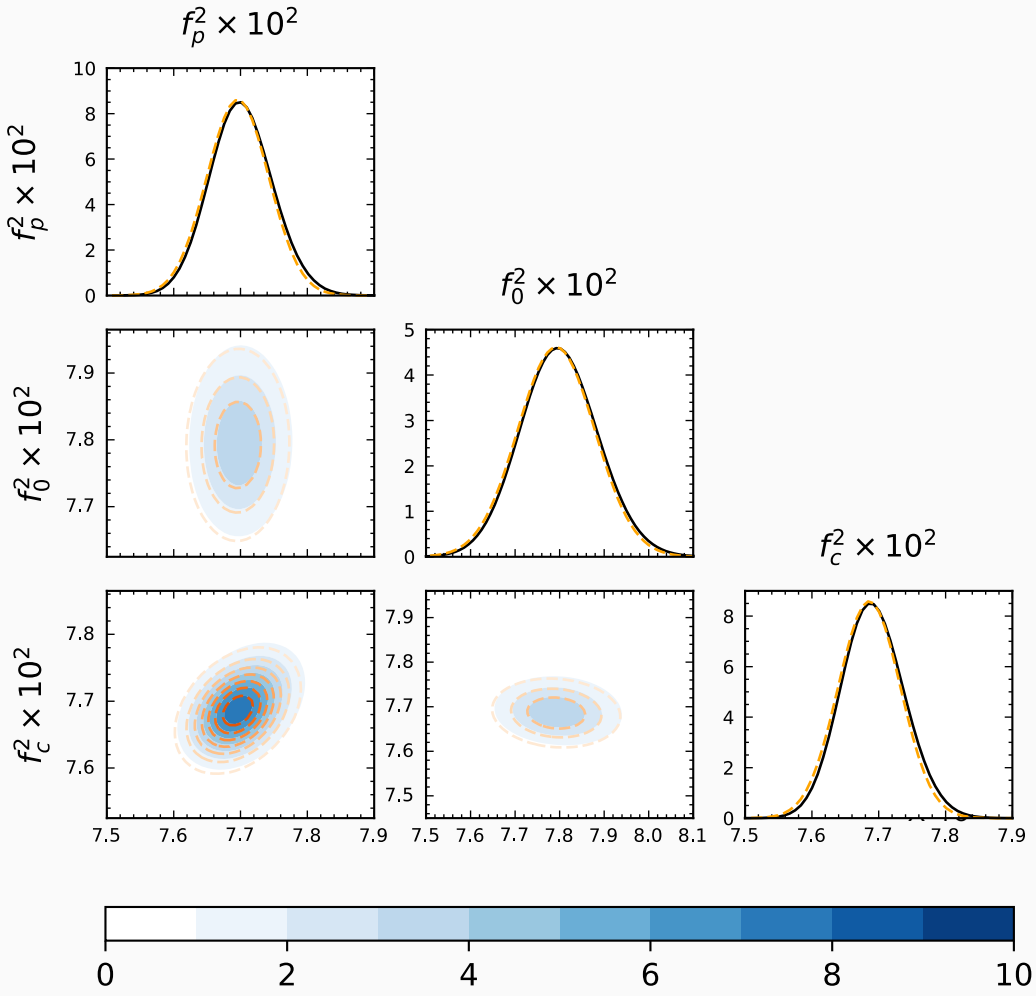
$$V_{1\pi}(pp) = f_p^2\, V_\pi(M_{\pi^0})$$
$$V_{1\pi}(np) = -f_0^2\, V_\pi(M_{\pi^0}) + (-1)^{t+1} 2 f_c^2\, V(M_{\pi^\pm})$$
$$V_{1\pi}(nn) = f_n^2\, V_\pi(M_{\pi^0})$$

with $\quad V_\pi(M_i) = -\dfrac{4\pi}{M_{\pi^\pm}^2} \dfrac{\vec{\sigma}_1 \cdot \vec{q}\, \vec{\sigma}_2 \cdot \vec{q}}{\vec{q}^2 + M_i^2}\ , \qquad f_0^2 = f_p f_n$

$$f_p^2 = \frac{M_{\pi^\pm}^2}{4\pi} \frac{g_A}{2F_\pi} \left[\frac{g_A}{2F_\pi} + \frac{2\epsilon M_\pi^2}{F_\pi} (2d_{17} - d_{18} - 2d_{19}) + (g_3 + g_4)\, e^2 F_\pi \right]$$
$$f_0^2 = \frac{M_{\pi^\pm}^2}{4\pi} \frac{g_A}{2F_\pi} \left[\frac{g_A}{2F_\pi} + \frac{g_4 e^2 F_\pi}{2} \right]$$
$$f_n^2 = \frac{M_{\pi^\pm}^2}{4\pi} \frac{g_A}{2F_\pi} \left[\frac{g_A}{2F_\pi} - \frac{2\epsilon M_\pi^2}{F_\pi} (2d_{17} - d_{18} - 2d_{19}) - g_3 e^2 F_\pi \right]$$
$$f_c^2 = \frac{M_{\pi^\pm}^2}{4\pi} \frac{g_A^2}{4F_\pi^2}$$

Effective $g_{A,\mathrm{eff}}$
$\equiv g_A - 2d_{18} M_\pi^2$

Results for πNN couplings [Phys. Rev. Lett. 126.092501 (2021)]



Determine f_i^2's from NN data

$$f_p^2 = 0.0770(5)(0.8)^\dagger$$
$$f_0^2 = 0.0779(9)(1.3)^\dagger$$
$$f_c^2 = 0.0769(5)(0.9)^\dagger$$

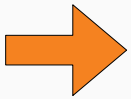
† Error due to πN LECs from Roy-Steiner analysis

- Integrate („marginalize“) posterior over Λ and short-range LECs
- Employ determined values for all cutoffs and all orders

Impact of IB on N⁴LO⁺ potential fit

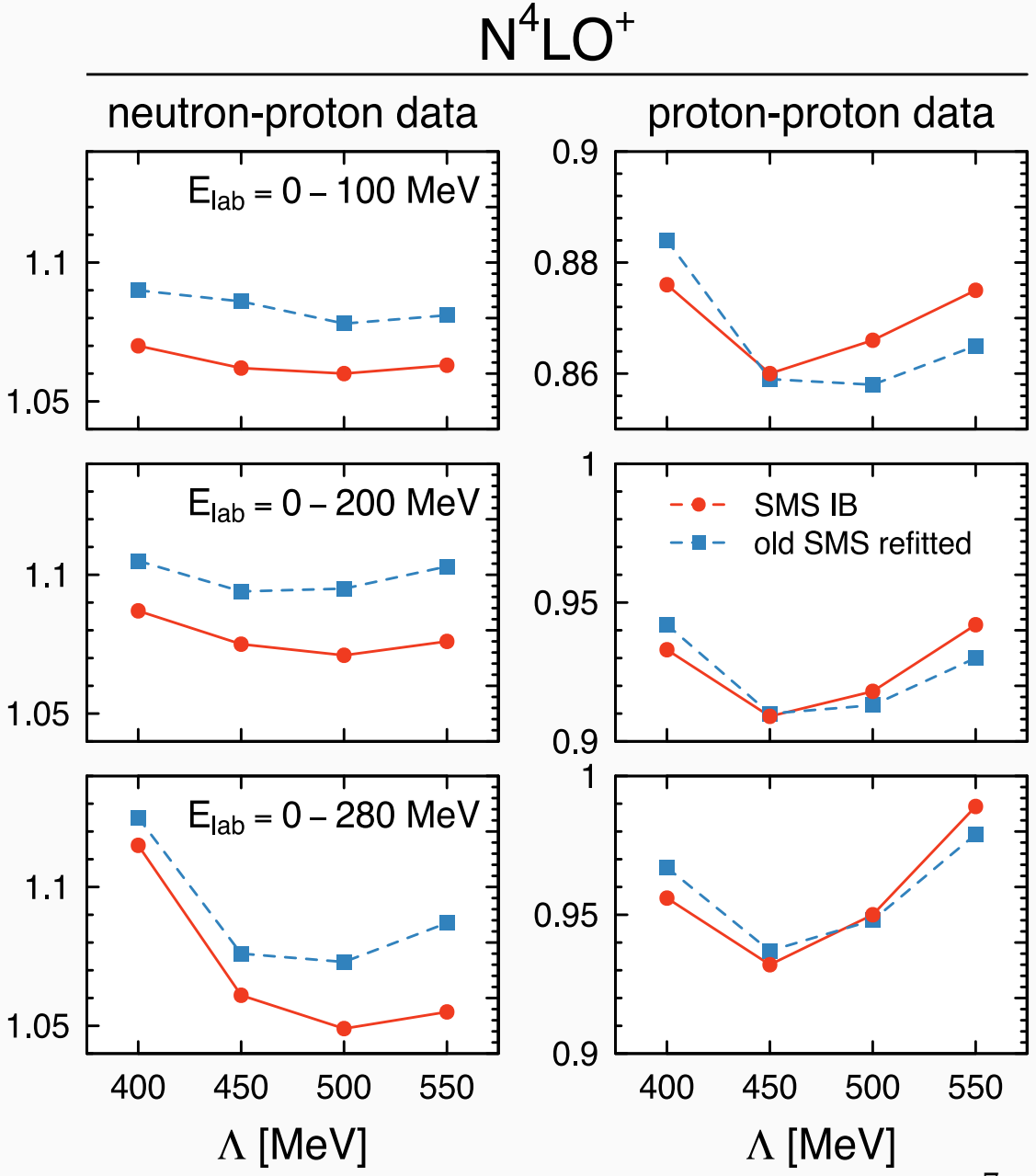
χ^2/datum pp+np, Λ = 450 MeV
E_{lab} = 0-280 MeV:

Without additional IB effects
1.018



With additional IB effects
1.007

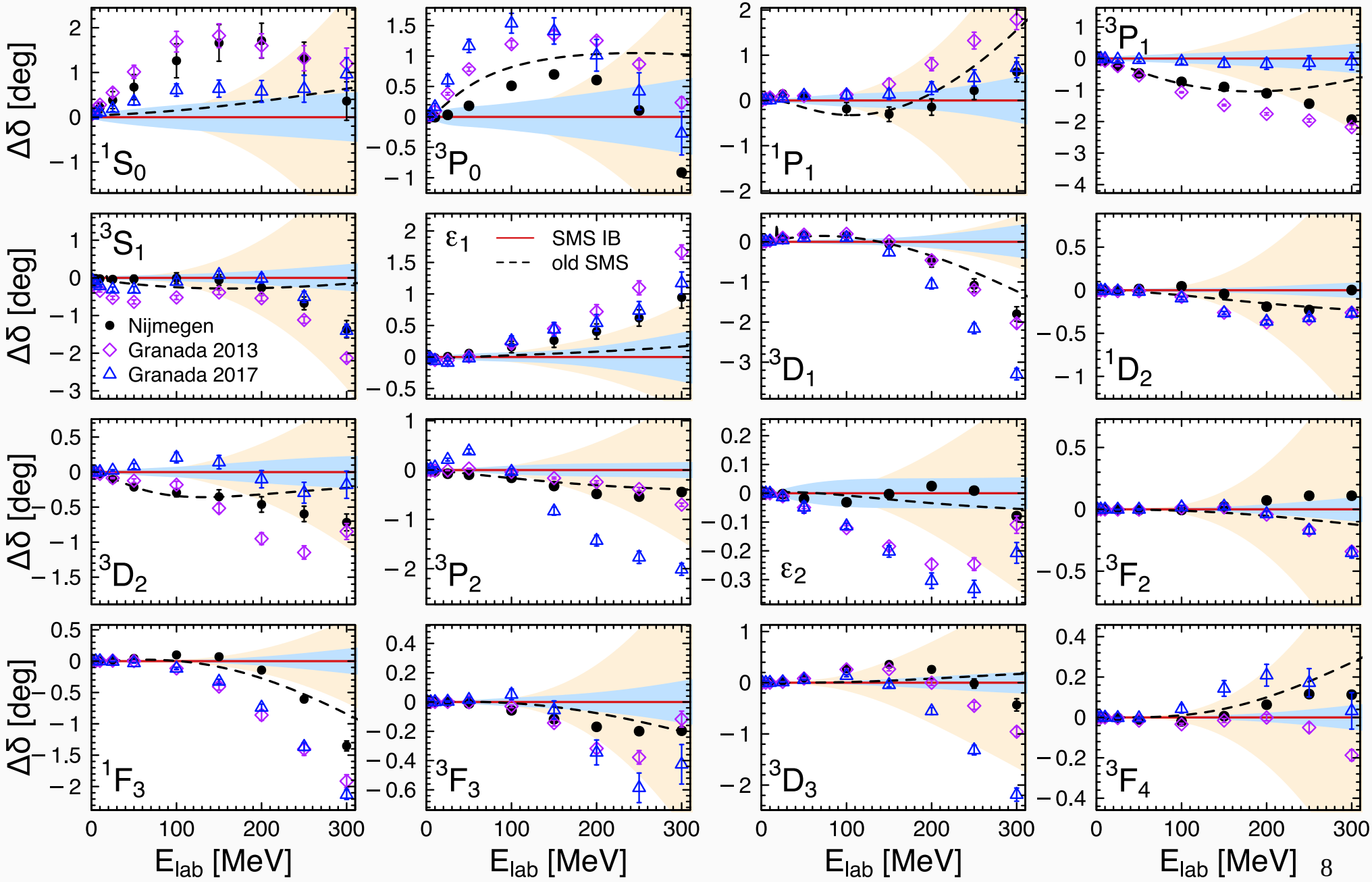
+ 6 parameters



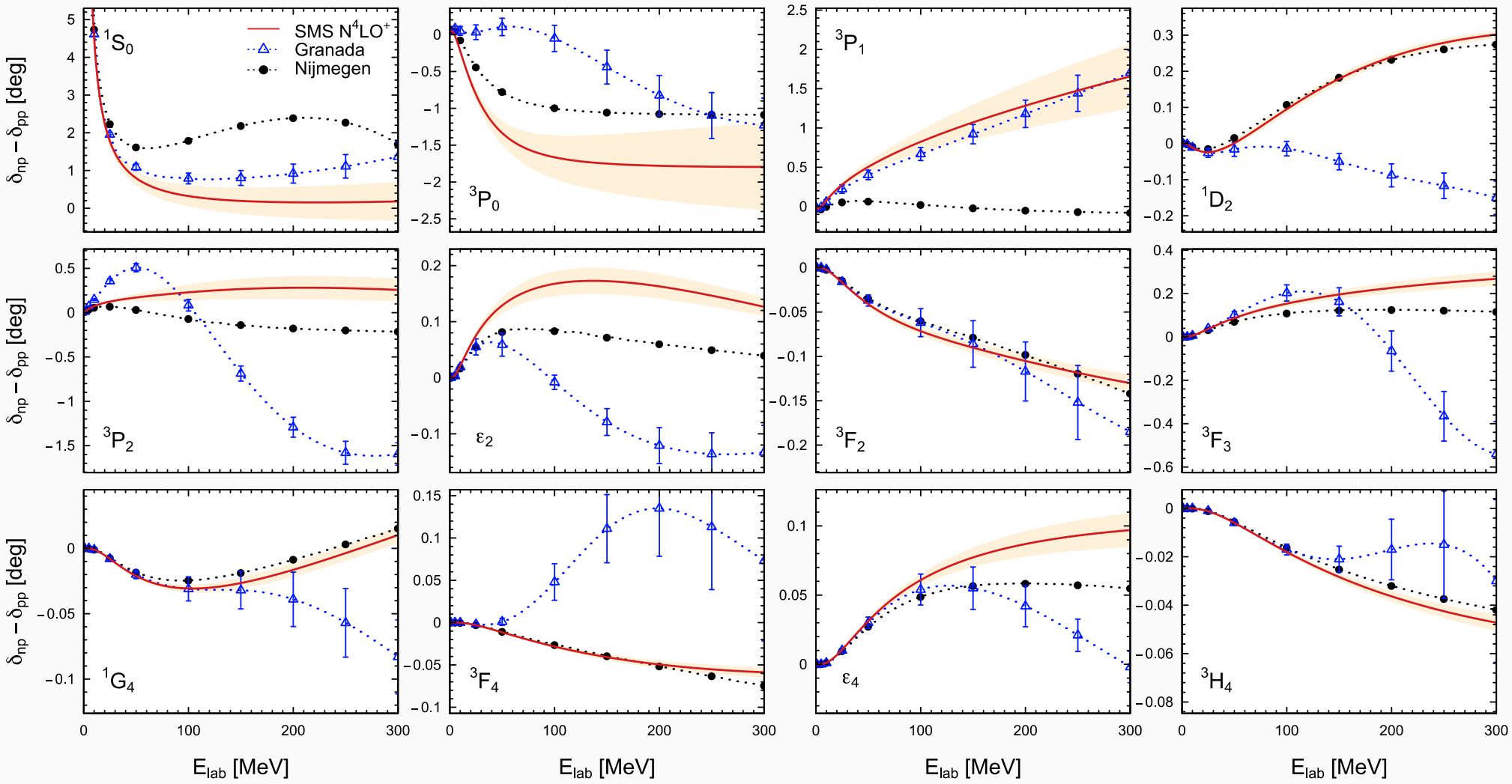
Database

- (minor) cleanup of full database (+ additions)
- performed own selection of mutual compatible data @ N⁴LO⁺

Neutron-Proton Phaseshifts N⁴LO⁺ (Λ = 450 MeV)

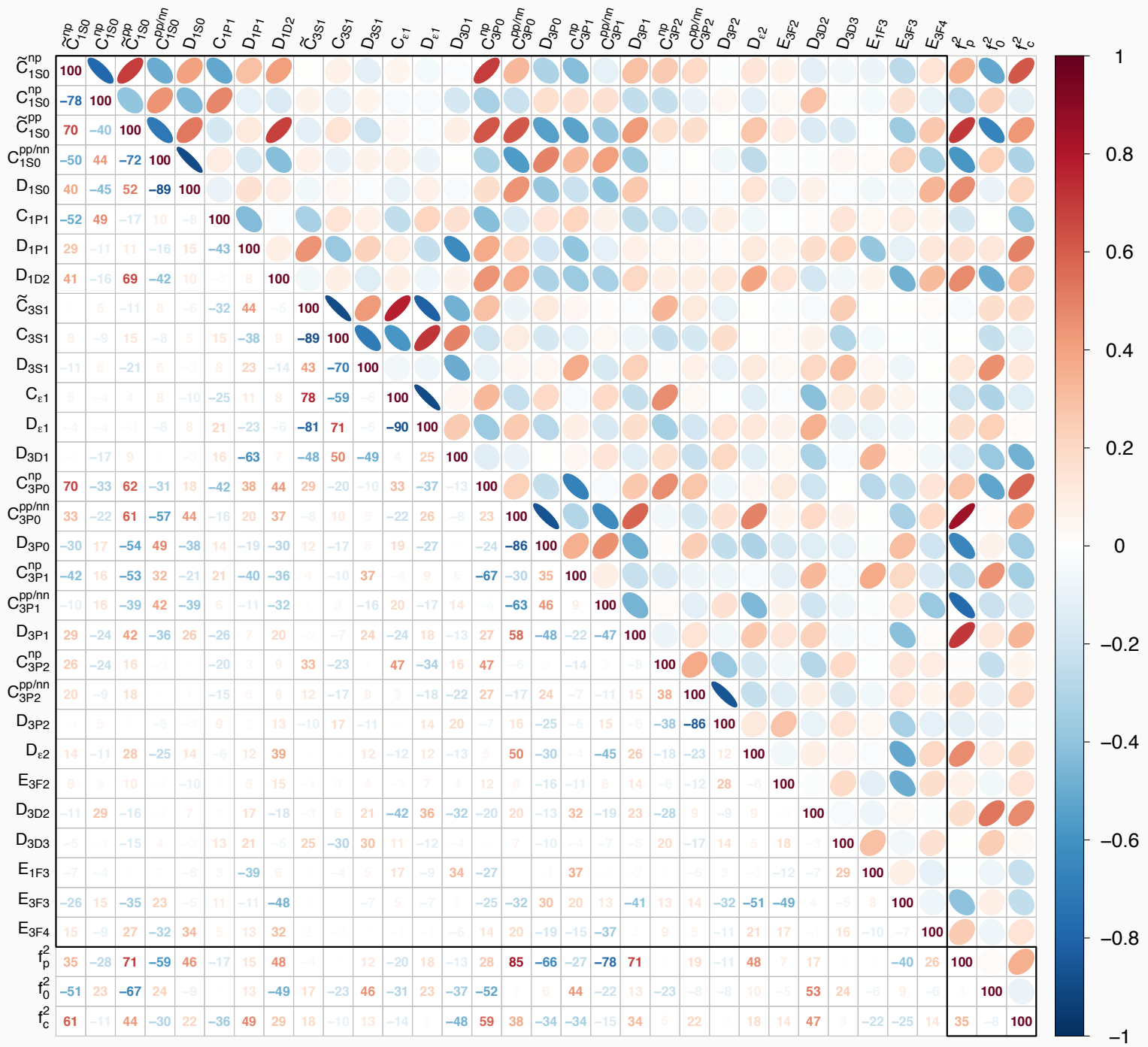


np-pp phaseshift difference N⁴LO⁺ (Λ = 450 MeV)



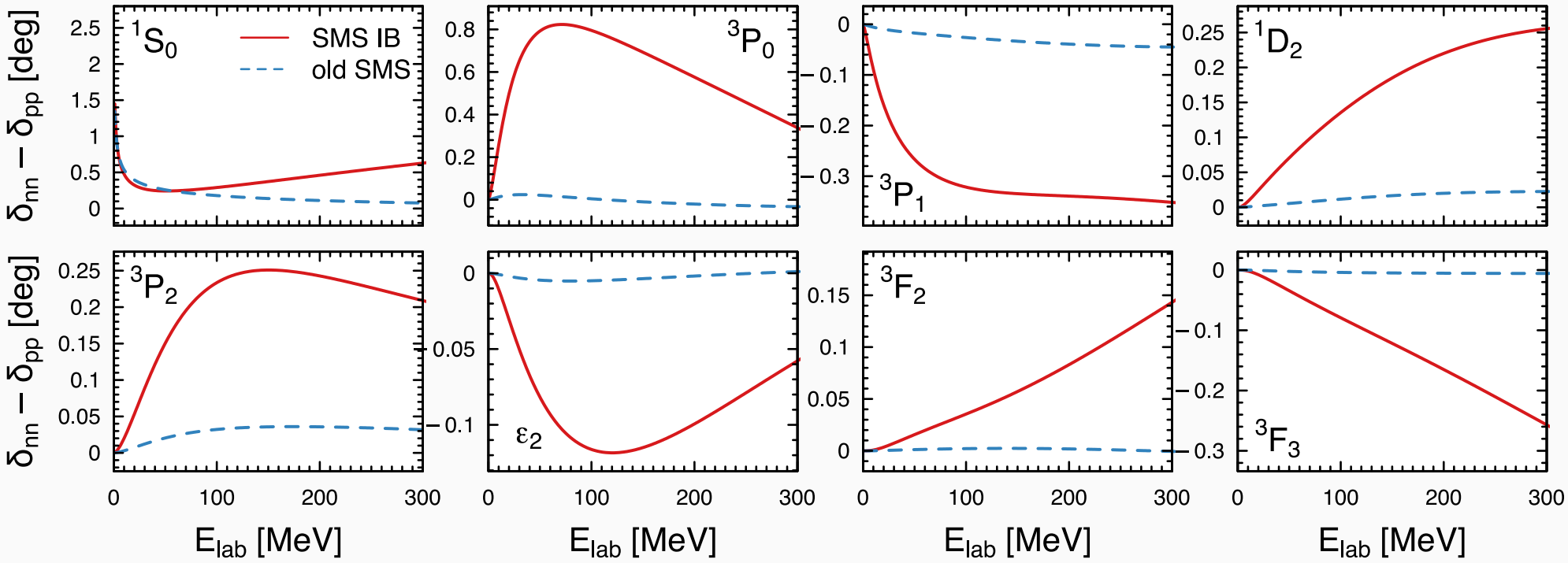
- Bands are statistical errors
- Includes Coulomb

Joint Covariance Matrix N⁴LO⁺ (Λ = 450 MeV)



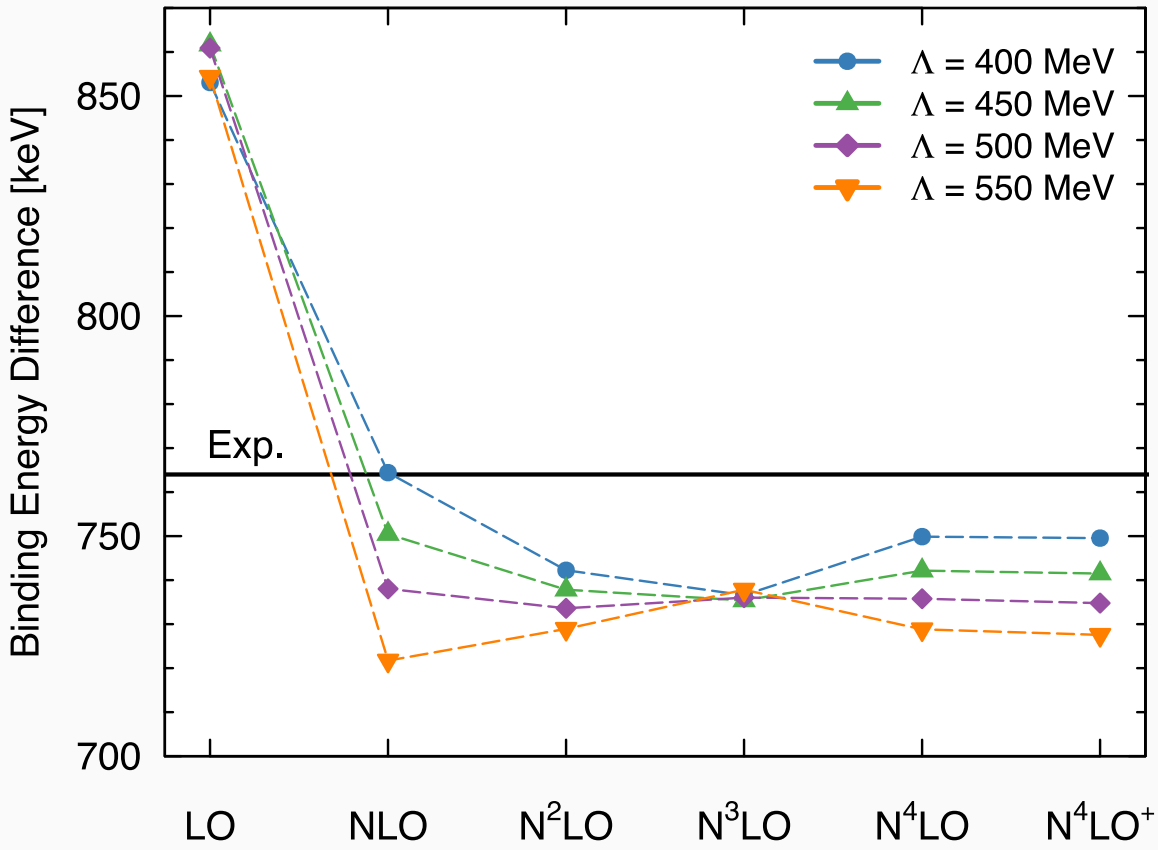
Neutron-neutron interaction

- From *pp* and *np* data, we get $f_n^2 = 0.0789(18)(3)$
- Due to the lack of experimental *nn* data, we currently cannot determine the subleading charge-dependent S- and P-wave contacts @ N^{4}LO
- Fix *nn*-*pp* phaseshift difference from Bonn model [Phys. Rev. C 58, 1393] and a_{nn} = -18.9 fm



- (large) uncertainty from $f_p^2 - f_n^2 = -0.0019(20)(4)$!

^{3}H-^{3}He binding energy difference



exp. E_{3H}-E_{3He} = 764 keV

- 3NF incomplete for N^{3}LO and above
- Neutron-proton mass difference in Faddeev equation adds ~ 10 keV @ N^{4}LO$^+$
- Electromagnetic effects beyond static Coulomb?

a_{nn} and ^{3}H-^{3}He binding energy diff. (Λ = 450 MeV)

a_{nn}	r_{nn} [fm]	E_{3H}-E_{3He} [keV]	E_{4He} [MeV]
-18.9 fm	2.835	741	28.21
-16.3 fm	2.795	736	28.26
20 fm	2.787	720	26.21

-16.3 fm:

- Bonn group nd breakup result, in conflict with TUNL result

➡ not *per se* ruled out by 3N binding energy difference

20 fm:

- bound Di-Neutron with E ~ 120 keV
- Investigation of symmetric space-star configuration breakup **[Phys. Rev. C 104.014002]**
- unnaturally large LECs!

Summary and Outlook

1. Extended SMS interaction with additional isospin-breaking effects up to N^4LO
2. Small improvement in neutron-proton scattering
3. Lack of data for neutron-neutron interaction. Partly fixed from Bonn model. A better method of determination would be desirable.
4. Investigation of current freedom in neutron-neutron interaction, e.g. with respect to tetra-neutron