Explicit Delta degree of freedom in Chiral two- and three-nucleon forces

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in collaboration with

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Outline

- ➔Introduction&Motivation
- ➔2-N forces with explicit Δ
- ➔3-N forces with explicit Δ
- ➔πN scattering with explicit Δ
- ➔Summary and Outlook

EFT with explicit $\Delta(1232)$

➔ Standard chiral expansion: $Q \sim M_\pi \ll \Delta \equiv m_\Delta - m_N = 293\mathrm{MeV}$

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- Δ gives a large contribution to LEC (c_3,c_4) via resonance saturation
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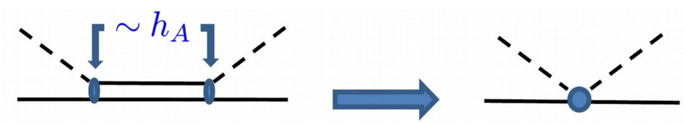

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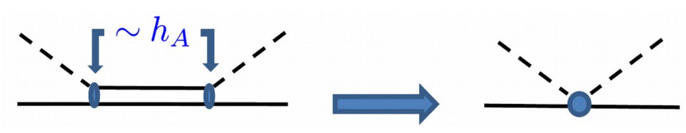
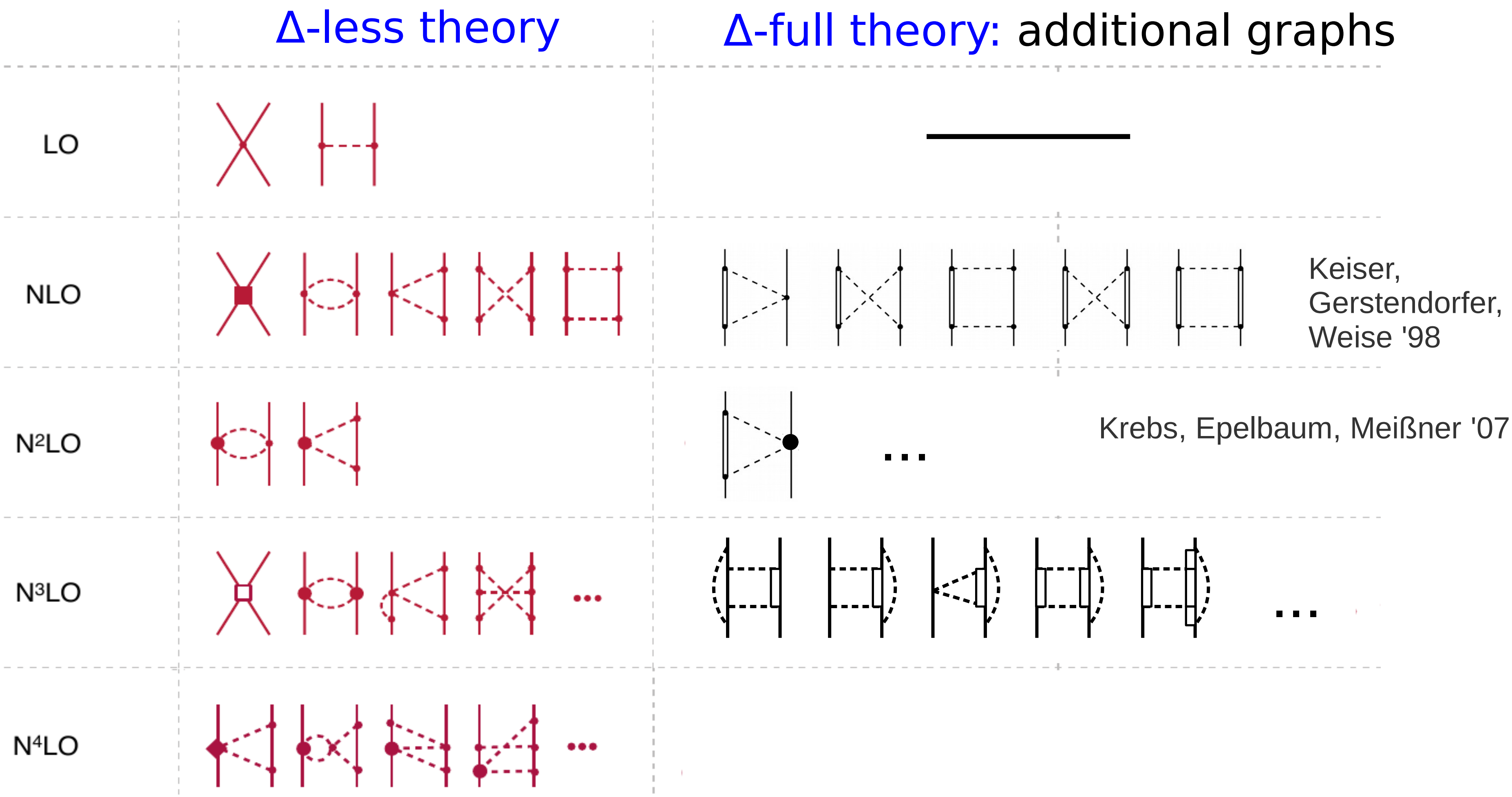


- Explicit decoupling of Δ makes comparison with Δ–less theory more transparent
  Bernard, Fearing, Hemmert, Meißner '98

finite parts of LECs can be always chosen such that $\lim_{\Delta \to \infty} = \Delta\text{–less}$
Appelquist, Carrazone '74 (Decoupling theorem)

Small scale expansion of 2NF



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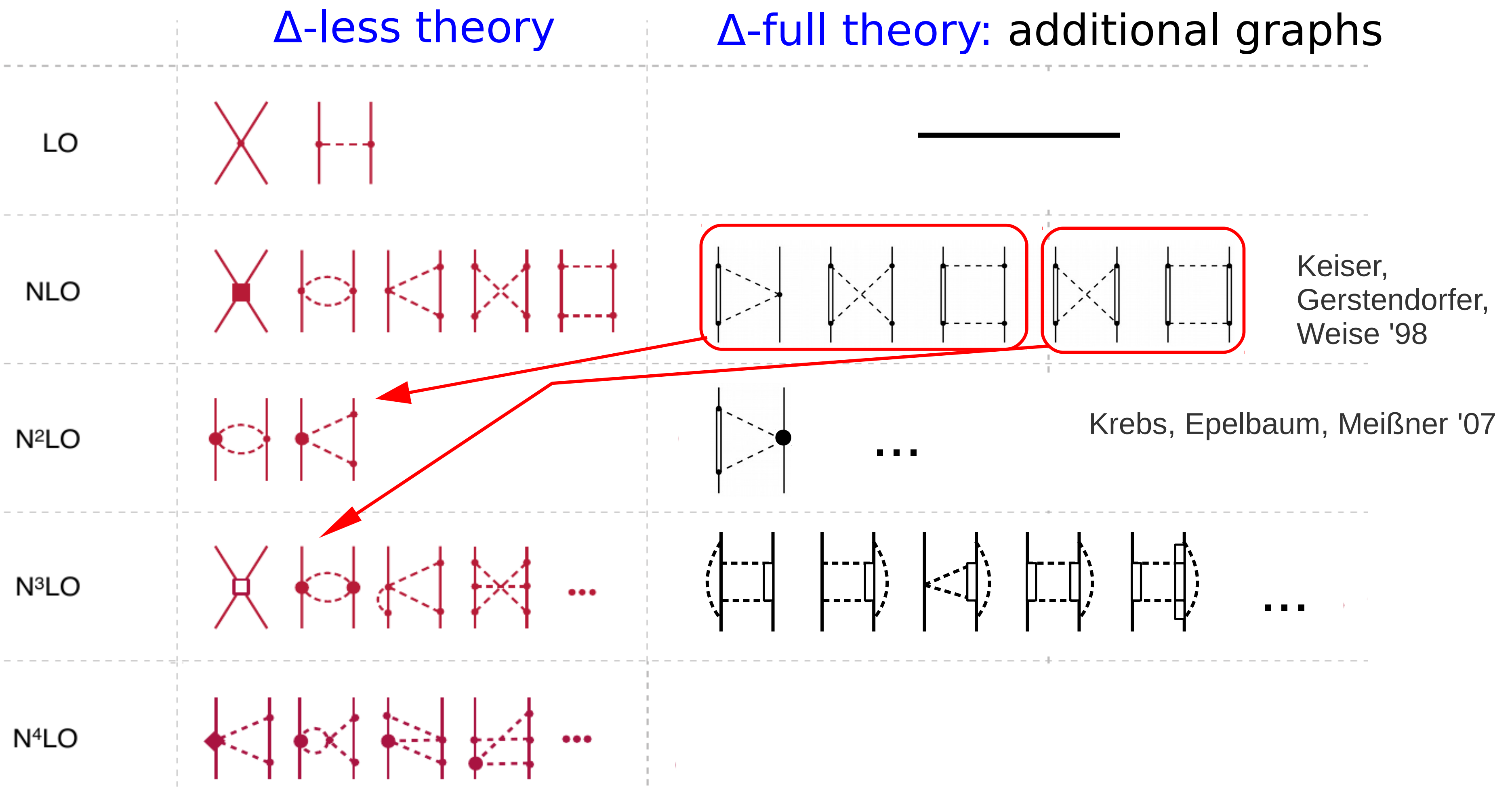

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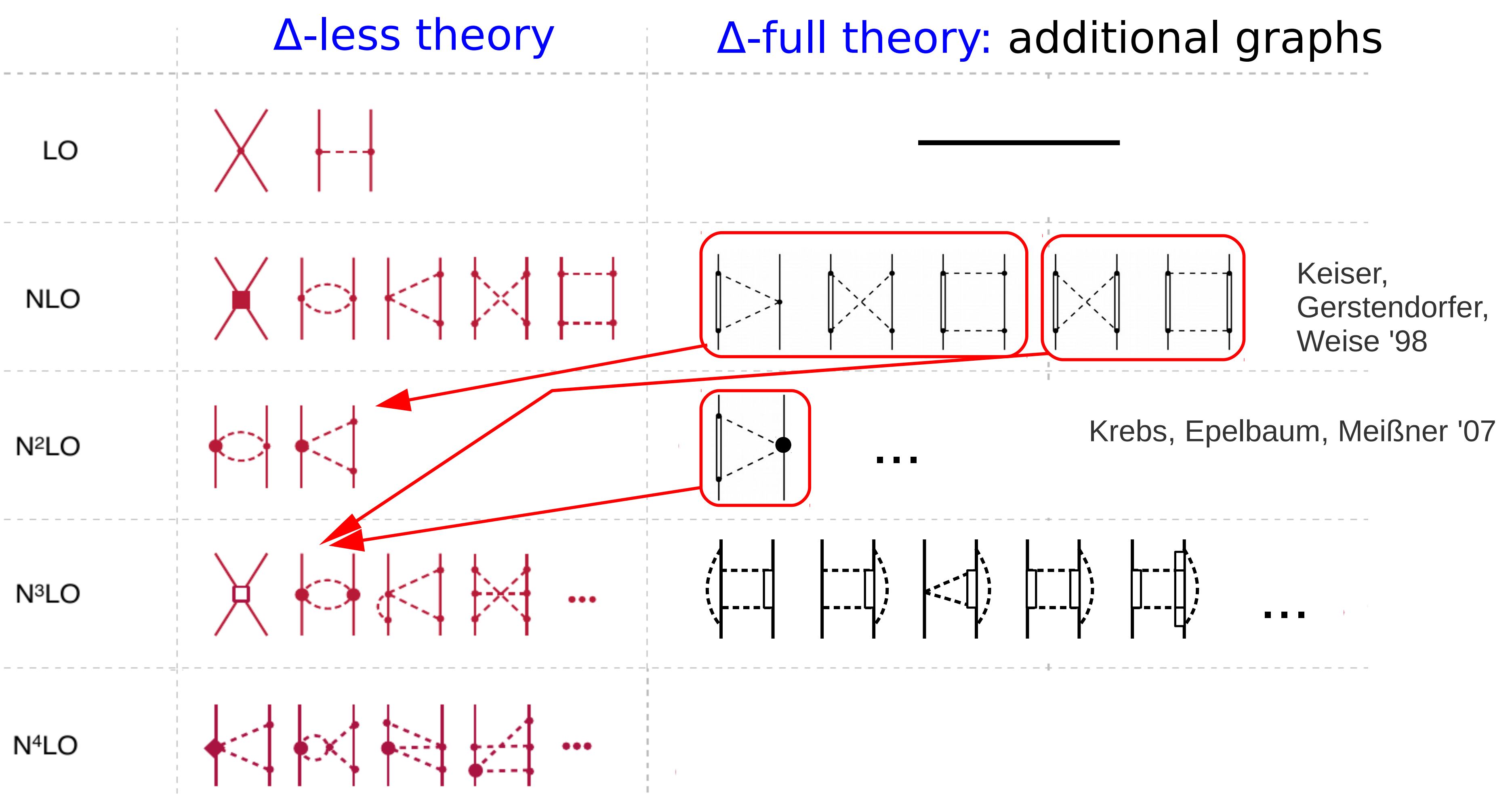

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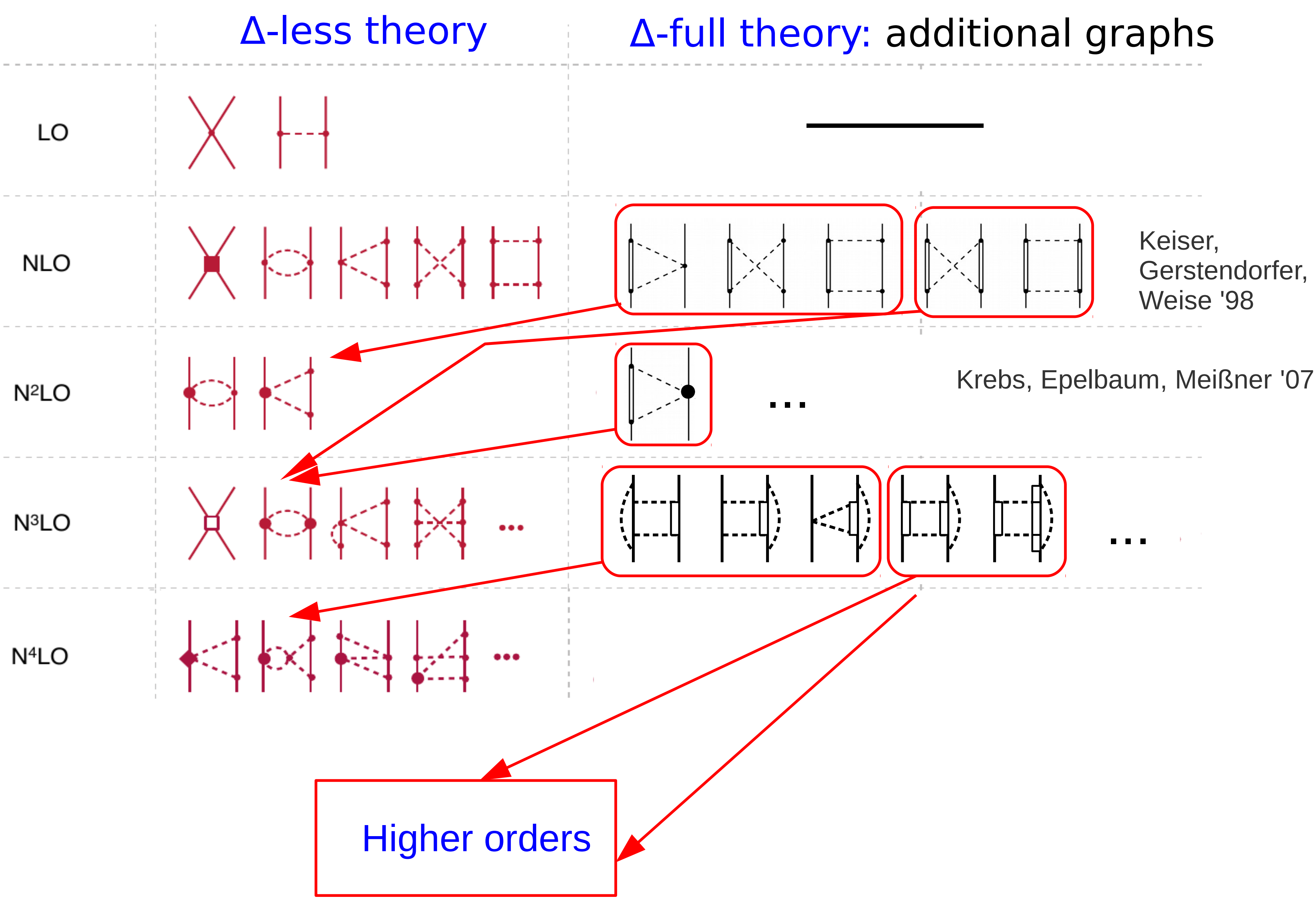
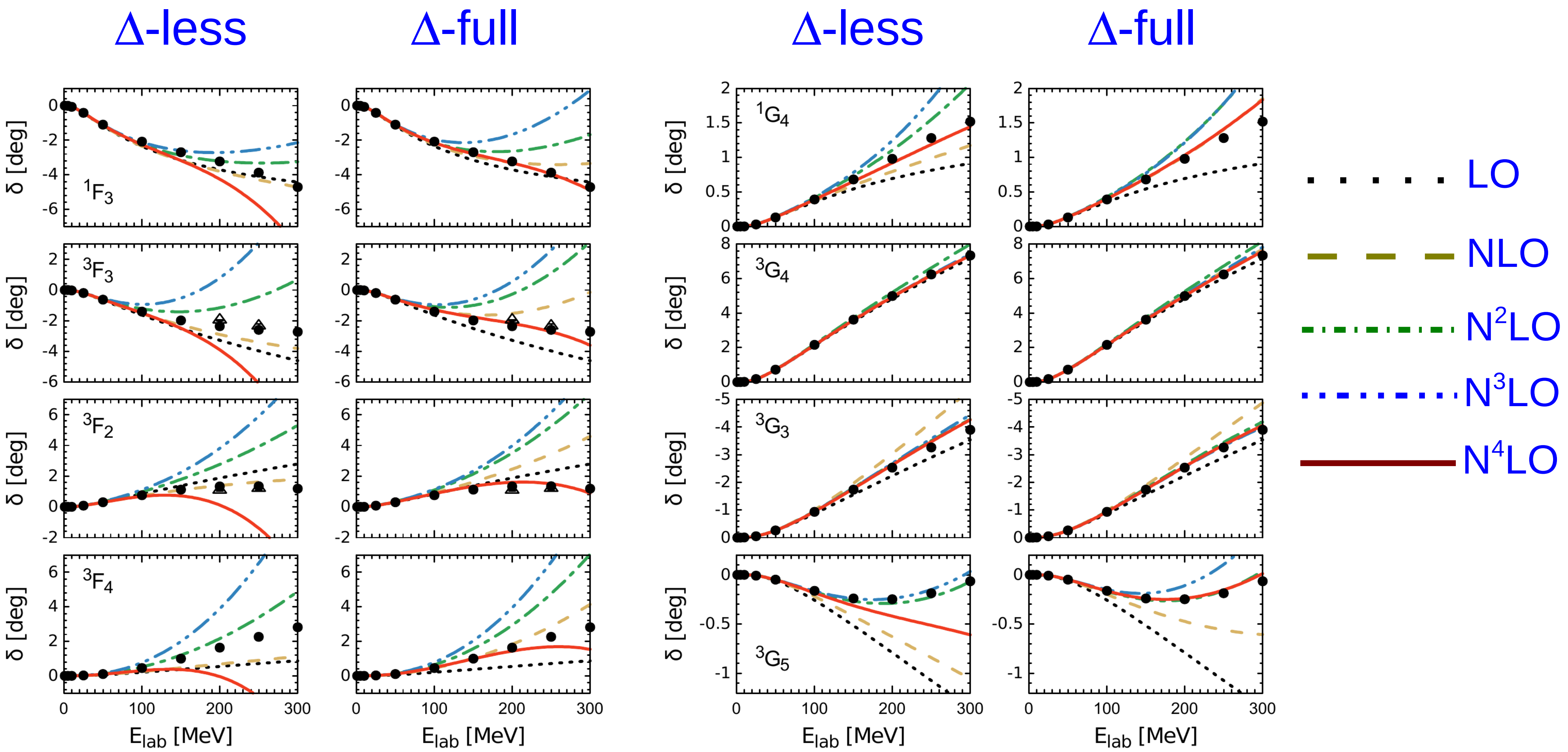


Preliminary results for N^3LO 2N forces with explicit Δ

- ➔ Only 2-pion-exchange contribution are considered (the long range part)
- ➔ $1/m_N$ corrections are not yet included
- ➔ Results for peripheral phases, no refitting of LEC's, no cut offs
- ➔ No additional parameters,
  h_A and g_1 ($\pi N\Delta$ and $\pi\Delta\Delta$)
  are extracted from the fit to πN scattering

F and G waves

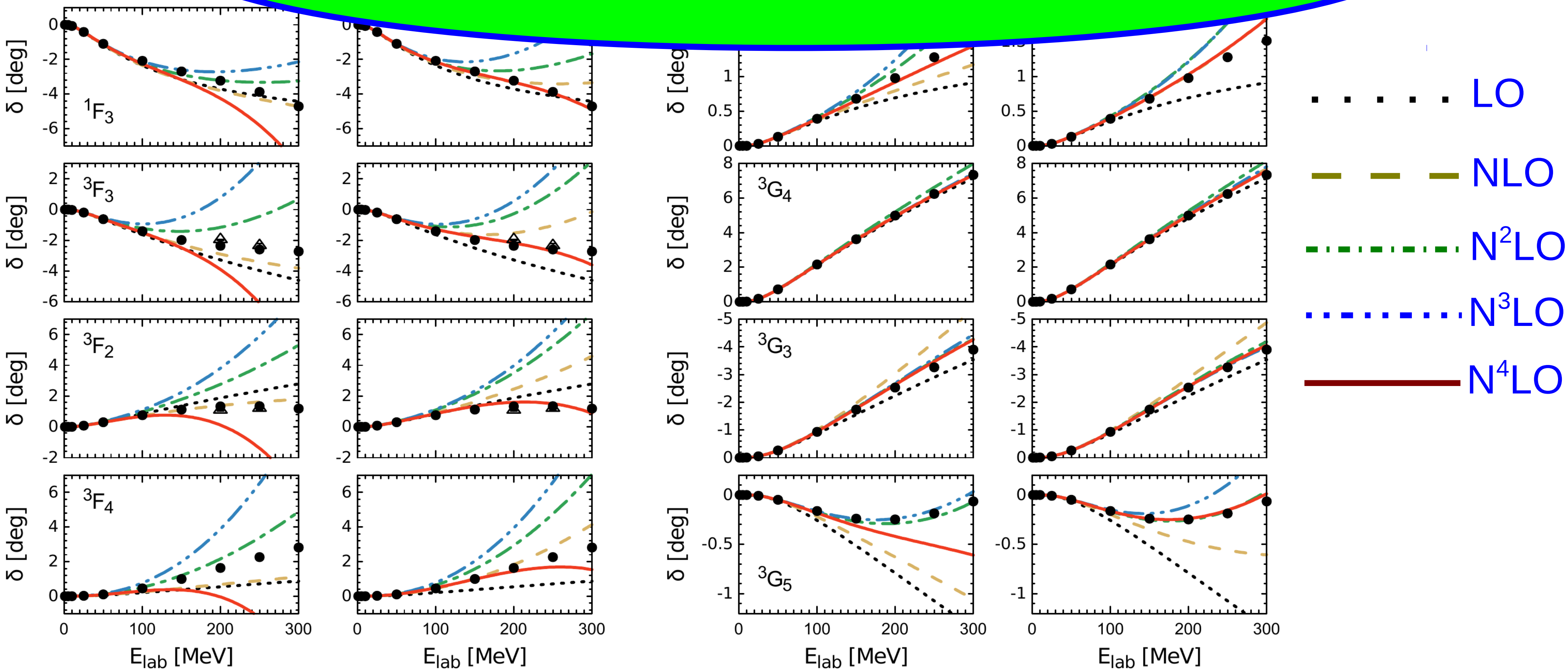


Data:Nijmegen PWA

F and G waves

Δ-

F-waves might be sensitive to the short-range physics



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F and G waves

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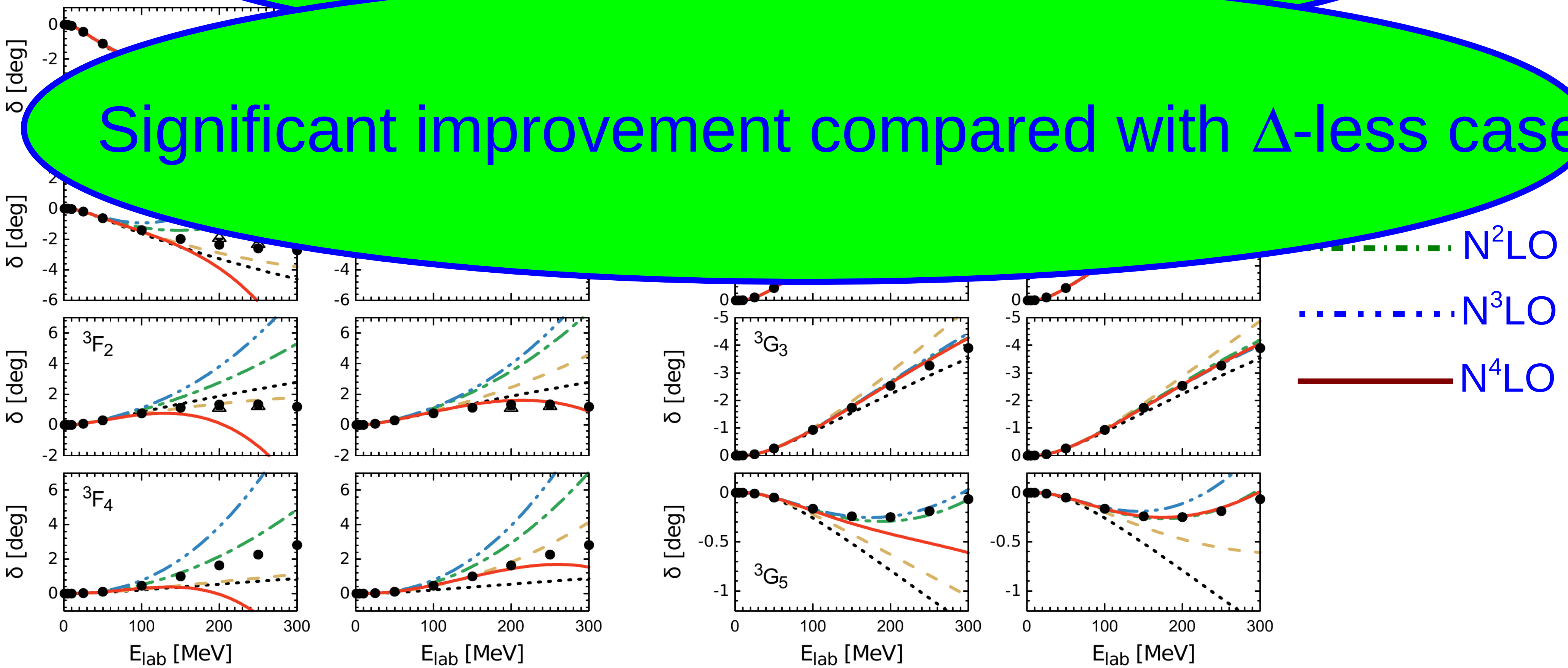
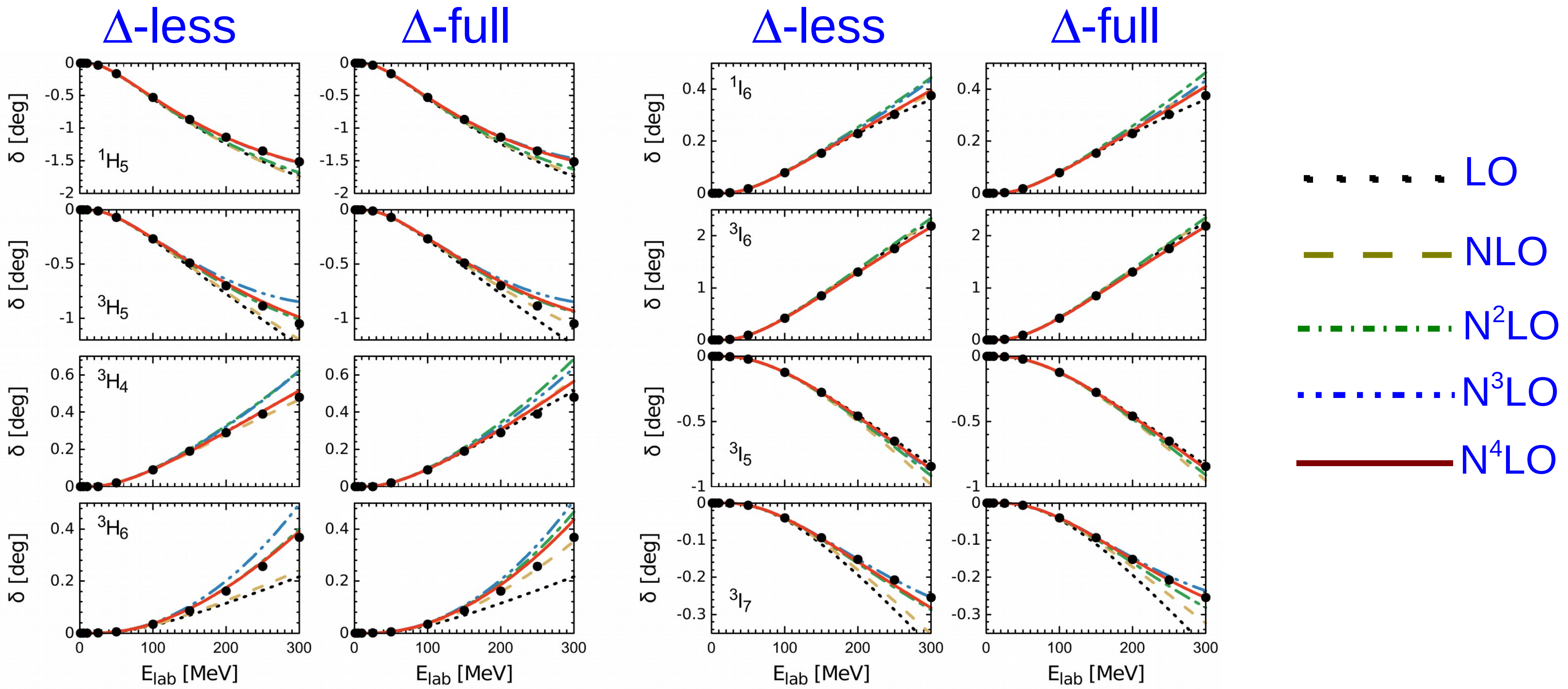
Significant improvement compared with Δ-less case



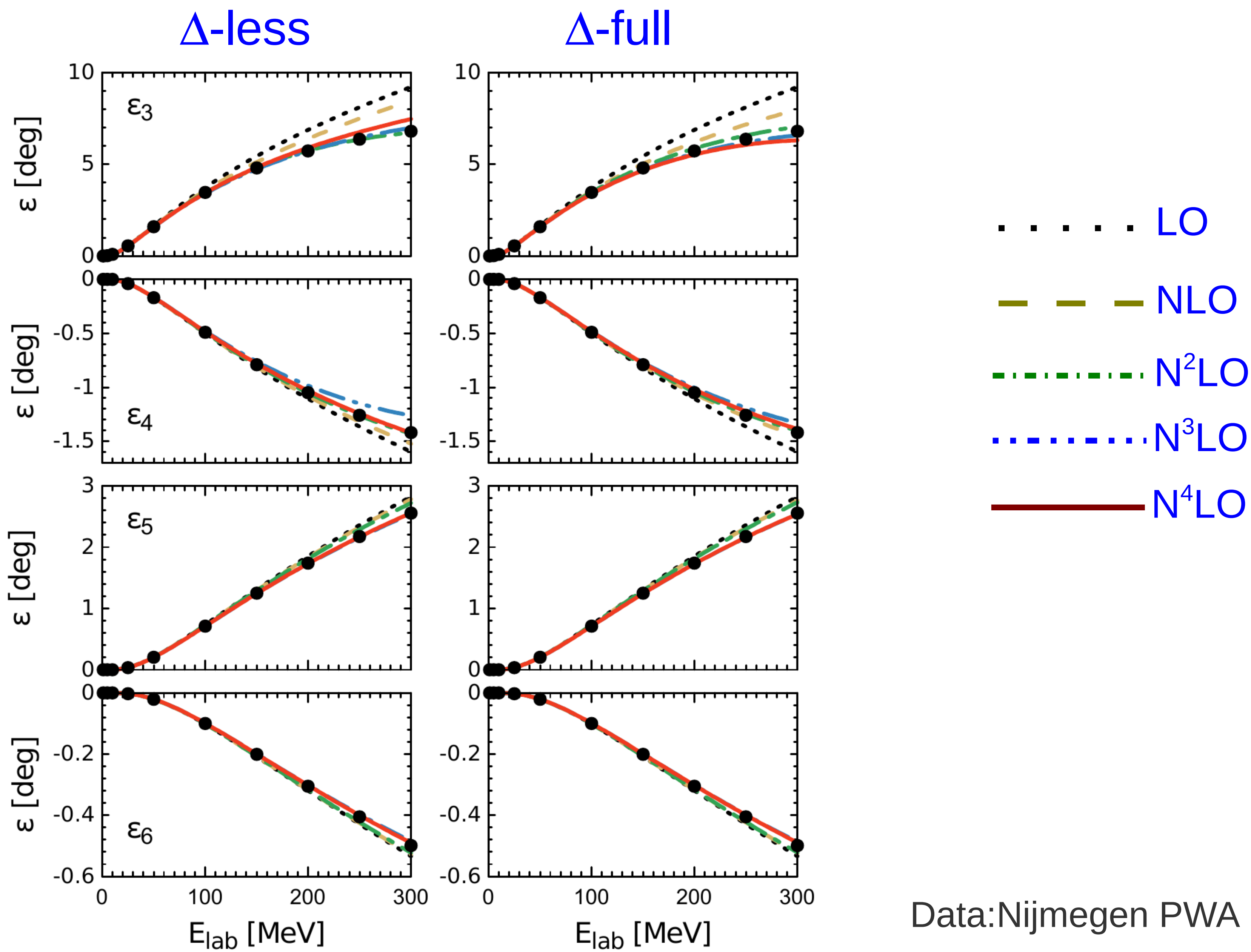
Data:Nijmegen PWA

H and I waves



Data:Nijmegen PWA

Mixing angles ε_3, ε_4, ε_5, ε_6



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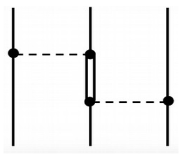
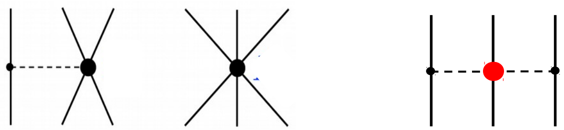
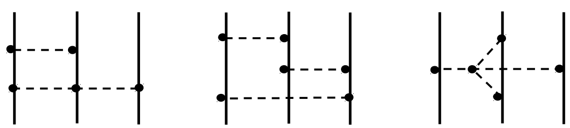
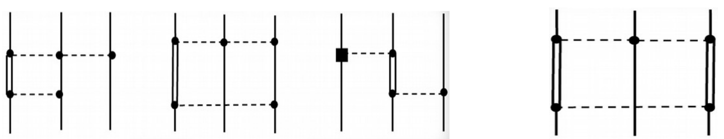
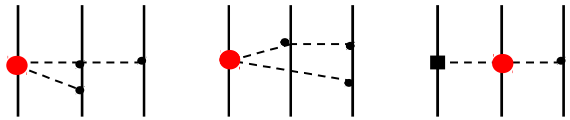
Small scale expansion of 3NF

	Δ-less theory	Δ-full theory: additional graphs
NLO	—	
N²LO		—
N³LO	 ...	 ...
N⁴LO	 ...	...

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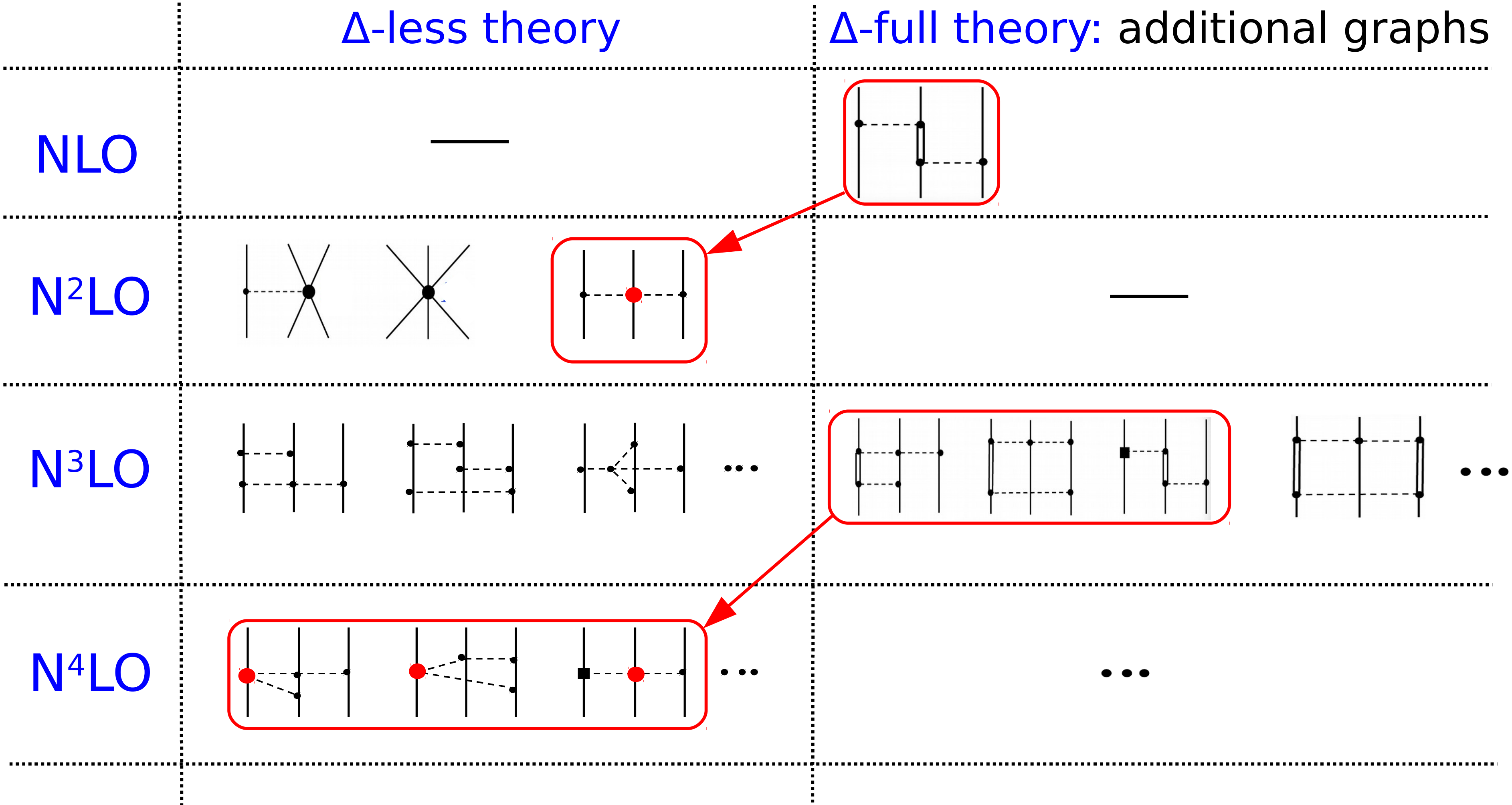

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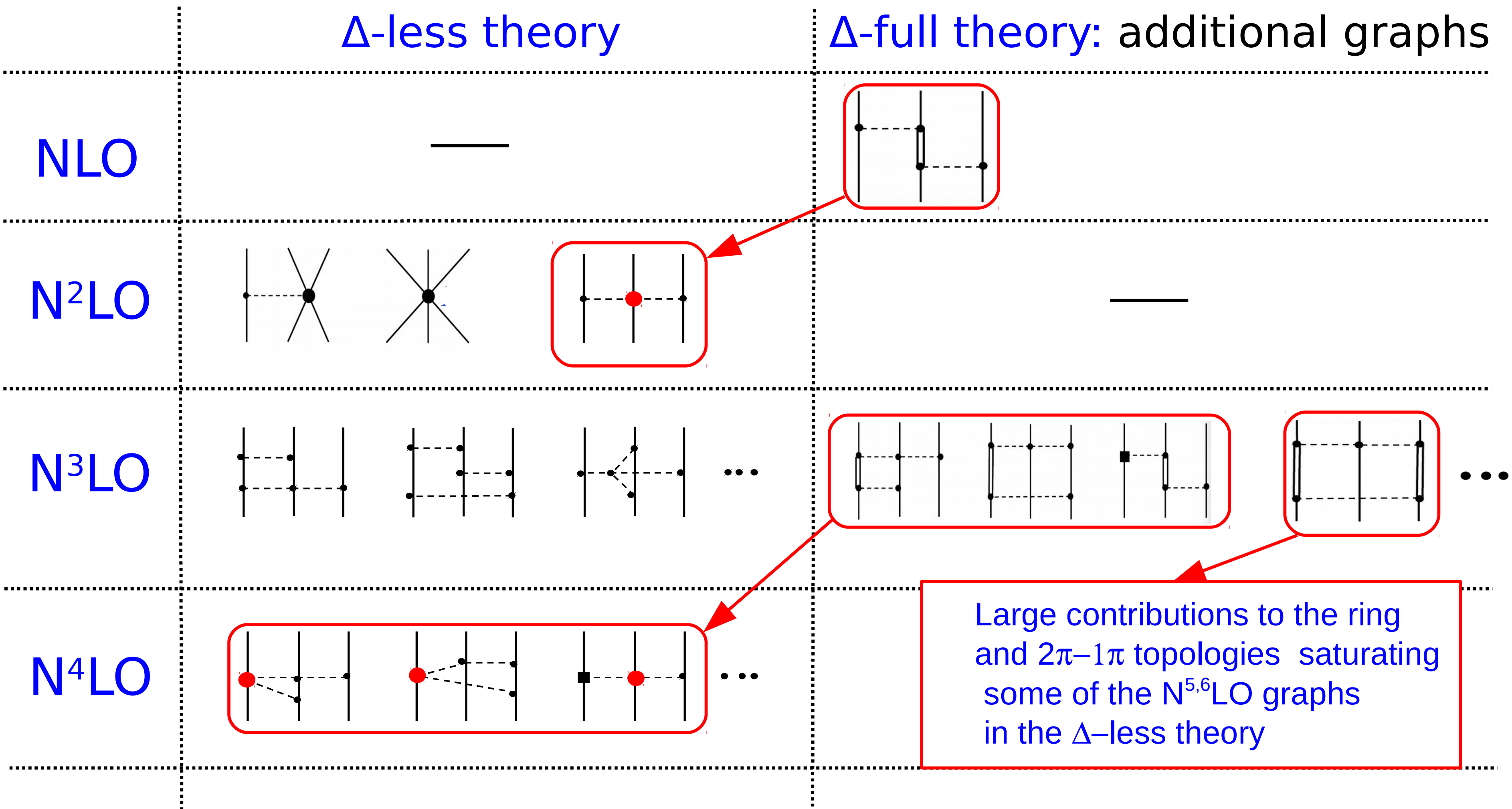
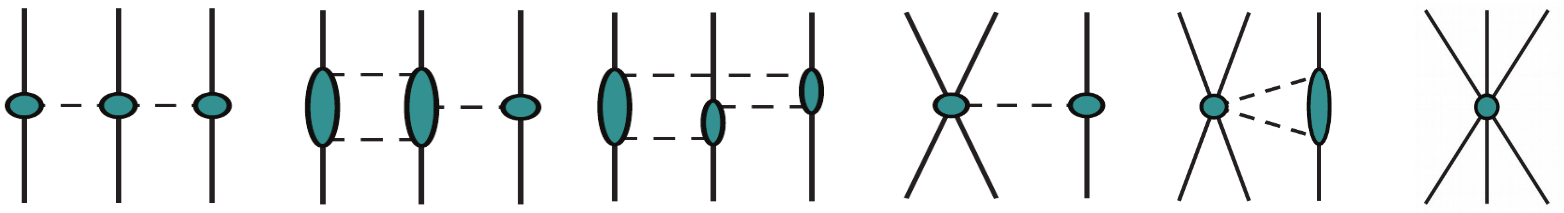


Long-range 3NF



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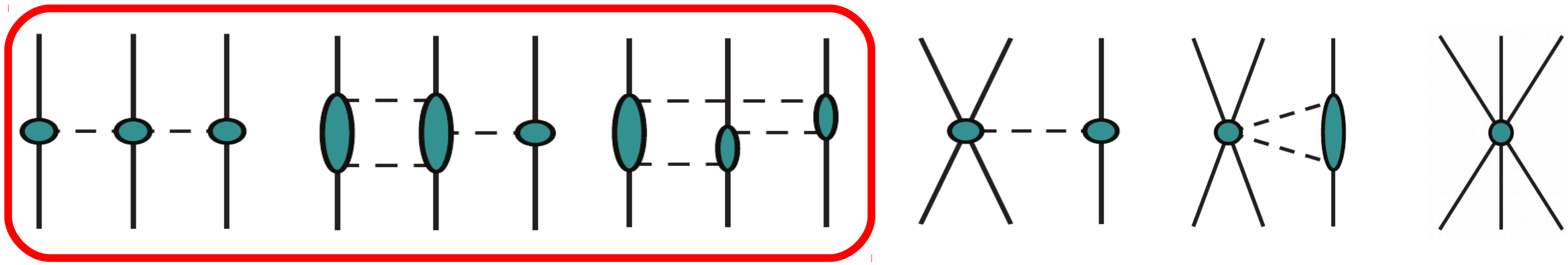
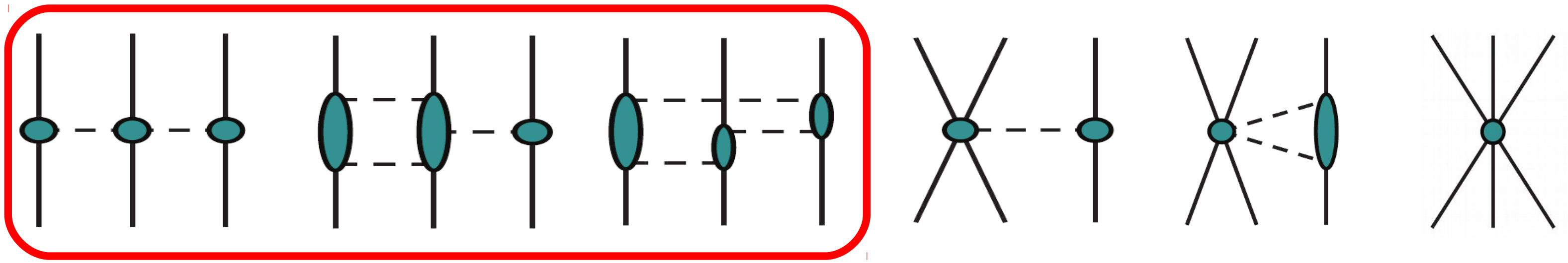


2π– exchange

2π–1π– exchange

ring

Long-range 3NF



2π–exchange   2π–1π–exchange   ring

➔ Only the long range part considered (coordinate space)

➔ Scheme independent

➔ No unknown parameters

Most general structure of a local 3NF

Krebs, AG, Epelbaum '13
Schat, Phillips '13
Epelbaum, AG, Krebs, Shat '15

Up to N^4LO all considered contribution are local

Constraints:
- Locality
- Isospin symmetry
- Parity and time-reversal invariance

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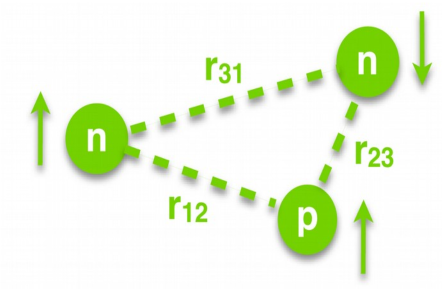

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$$
\begin{aligned}
\tilde{\mathcal{G}}_1 &= 1 \\
\tilde{\mathcal{G}}_2 &= \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \\
\tilde{\mathcal{G}}_3 &= \vec{\sigma}_1 \cdot \vec{\sigma}_3 \,, \\
\tilde{\mathcal{G}}_4 &= \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \vec{\sigma}_1 \cdot \vec{\sigma}_3 \,, \\
\tilde{\mathcal{G}}_5 &= \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \vec{\sigma}_1 \cdot \vec{\sigma}_2 \\
\tilde{\mathcal{G}}_6 &= \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3) \\
\tilde{\mathcal{G}}_7 &= \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23}) \\
\tilde{\mathcal{G}}_8 &= \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_3 \\
\tilde{\mathcal{G}}_9 &= \hat{r}_{23} \cdot \vec{\sigma}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \\
\tilde{\mathcal{G}}_{10} &= \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_3 \\
\tilde{\mathcal{G}}_{11} &= \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_2 \\
\tilde{\mathcal{G}}_{12} &= \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_2 \\
\tilde{\mathcal{G}}_{13} &= \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_2 \\
\tilde{\mathcal{G}}_{14} &= \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_2 \\
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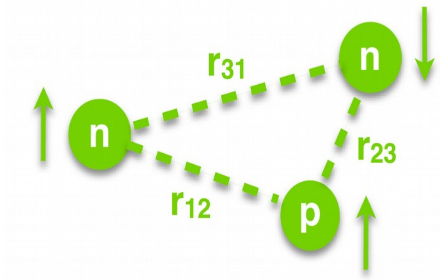
\tilde{\mathcal{G}}_{16} &= \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_2 \, \hat{r}_{12} \cdot \vec{\sigma}_3 \\
\tilde{\mathcal{G}}_{17} &= \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_3 \\
\tilde{\mathcal{G}}_{18} &= \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot \vec{\sigma}_3 \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23}) \\
\tilde{\mathcal{G}}_{19} &= \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_3 \cdot \hat{r}_{23} \, \hat{r}_{23} \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2) \\
\tilde{\mathcal{G}}_{20} &= \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot \hat{r}_{23} \, \vec{\sigma}_3 \cdot \hat{r}_{12} \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})
\end{aligned}
$$

Constraints:
- Locality
- Isospin symmetry
- Parity and time-reversal invariance

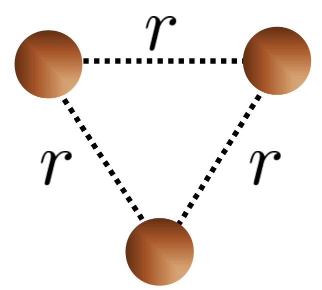


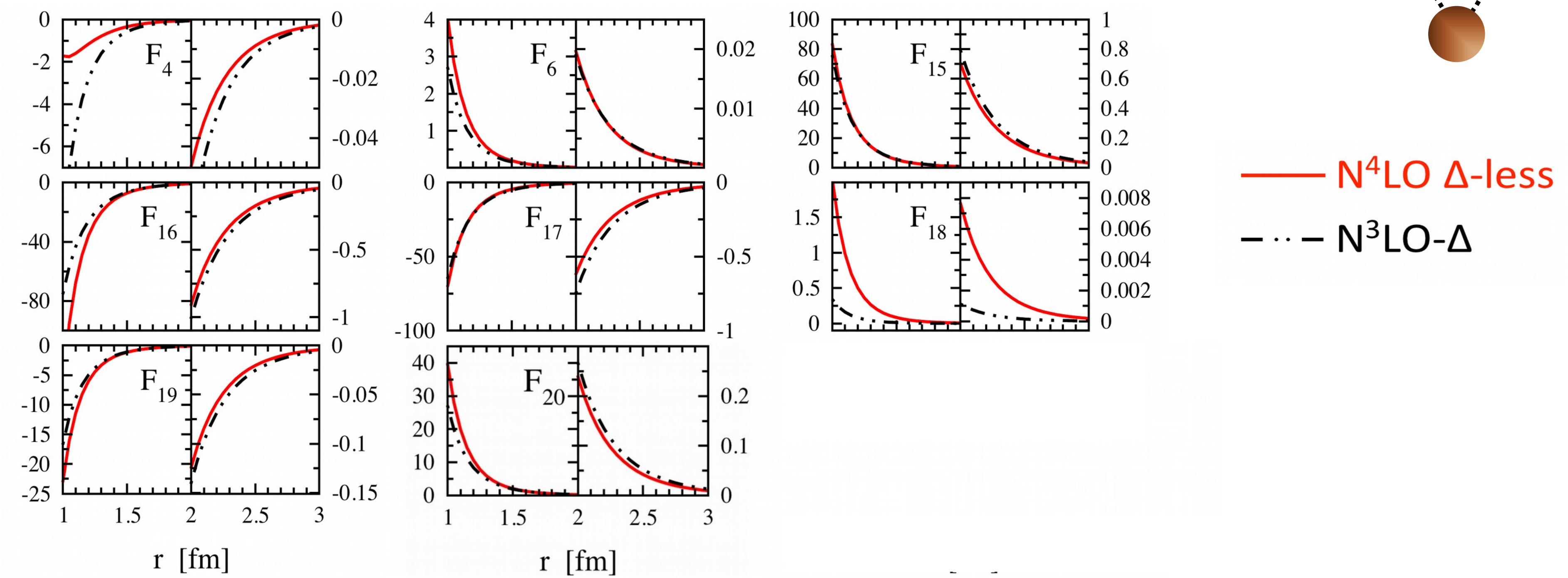
$$V_{3N} = \sum_{i=1}^{20} \tilde{\mathcal{G}}_i \, F_i(r_{12}, r_{23}, r_{31}) + 5\mathrm{perm}$$

Two-pion-exhcange 3NF in Δ–full and Δ–less approach (preliminary)

Krebs, AG, Epelbaum, in preparation

TPE "structure functions" F_i in MeV"
in equilateral-triangle configuration





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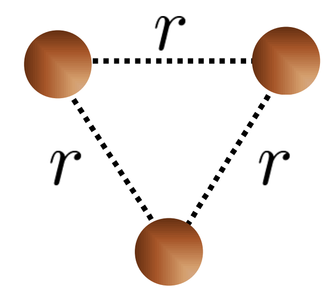

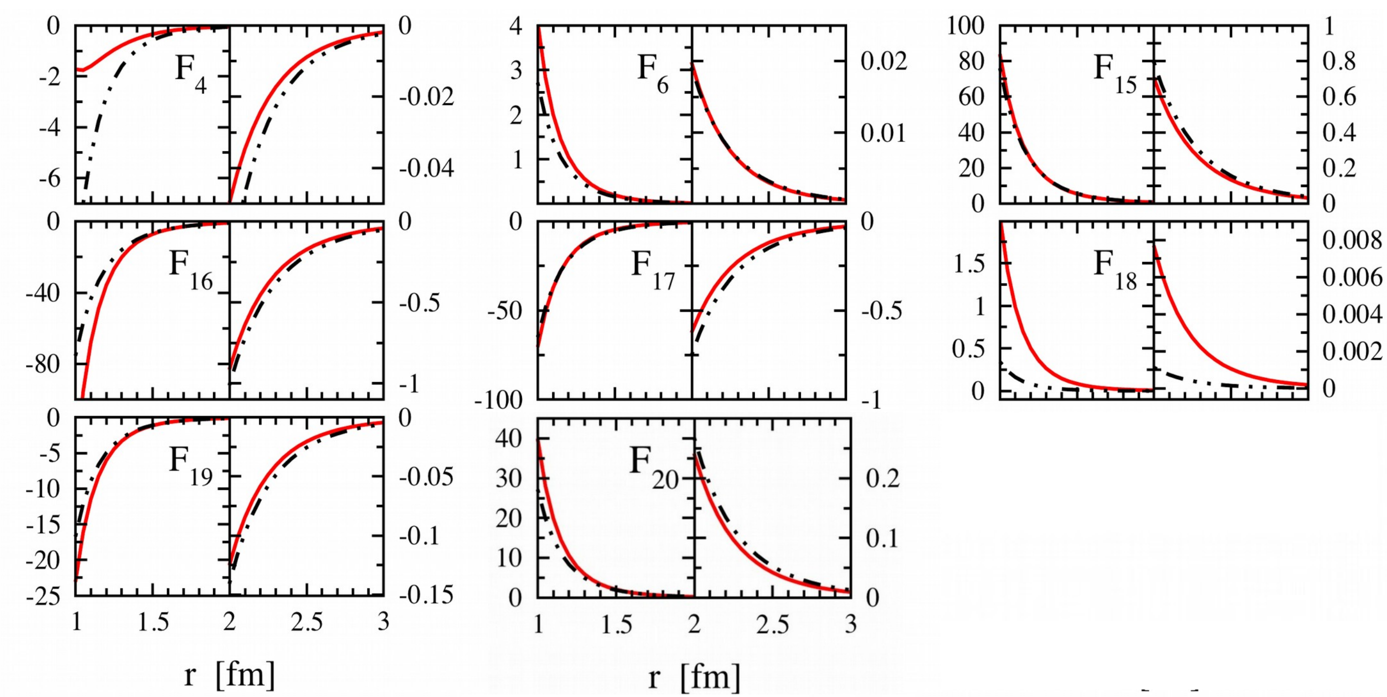

N⁴LO Δ-less
N³LO-Δ

➔ similar results for large contributions

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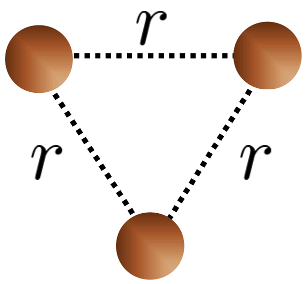
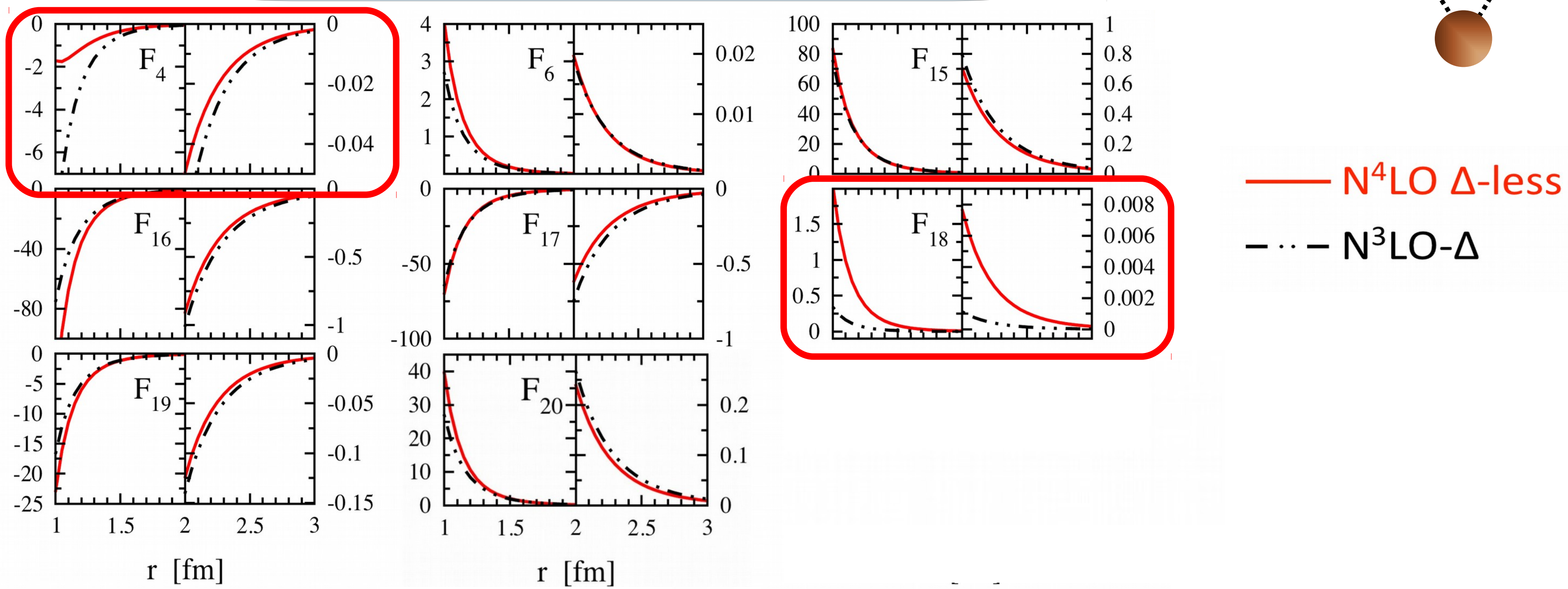
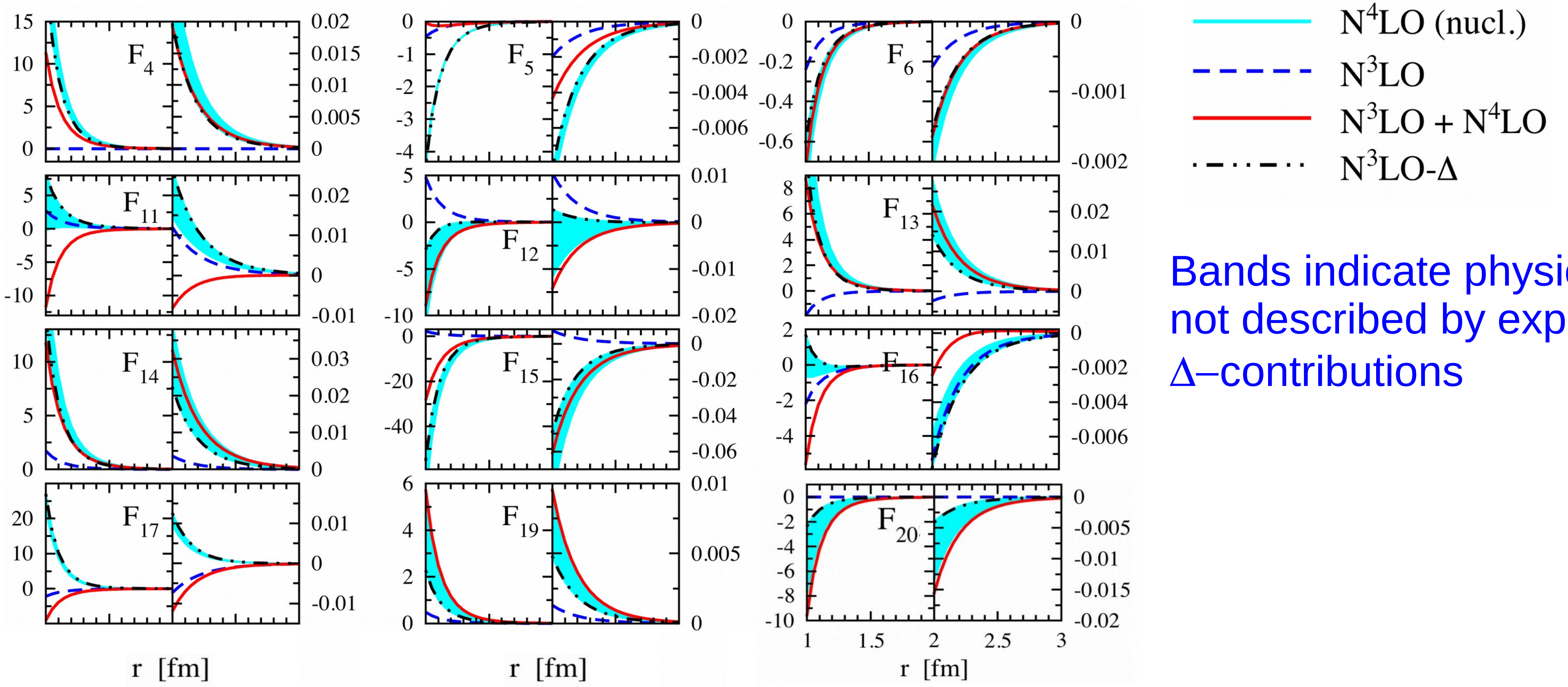




➔ similar results for large contributions

➔ slightly different for small contributions

Two-pion-one-pion-exhcange 3NF in Δ–full and Δ–less approach (preliminary)



Bands indicate physics not described by explicit Δ–contributions

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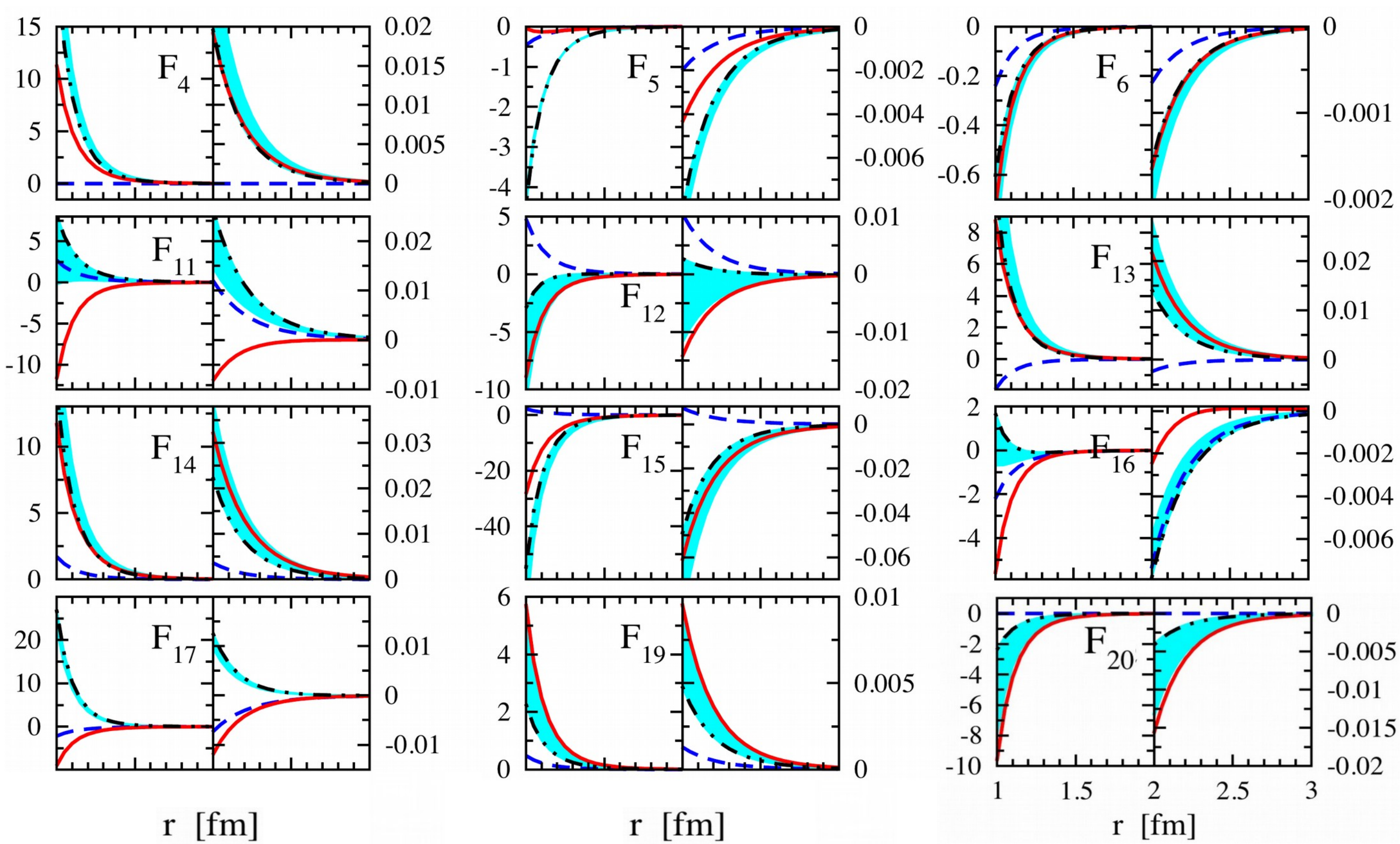

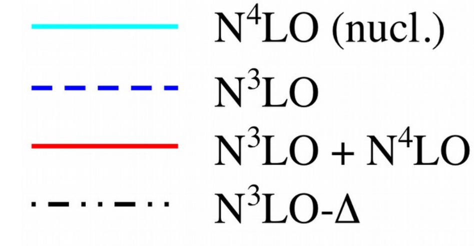

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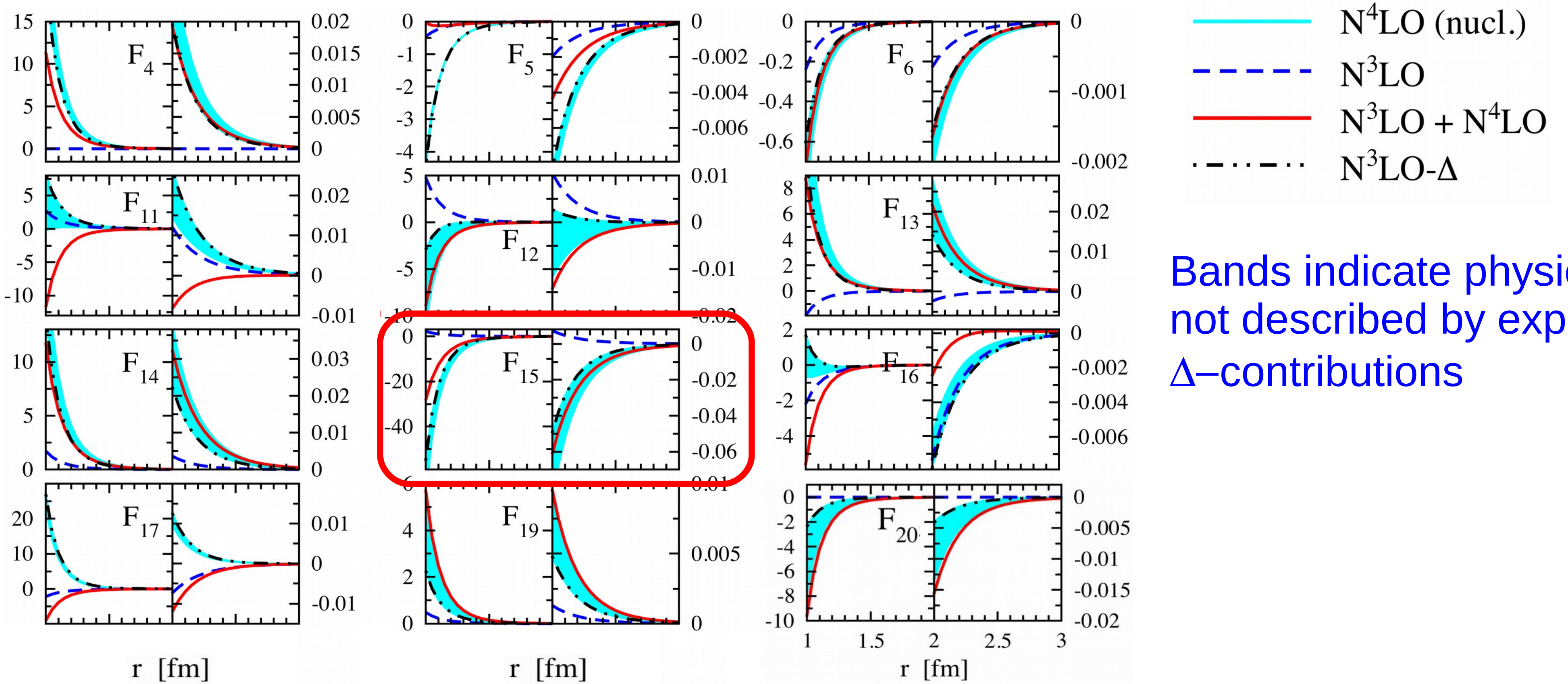
➔ Dominant effects come from N^3LO-Δ/N^4LO

Two-pion-one-pion-exhcange 3NF in Δ–full and Δ–less approach (preliminary)

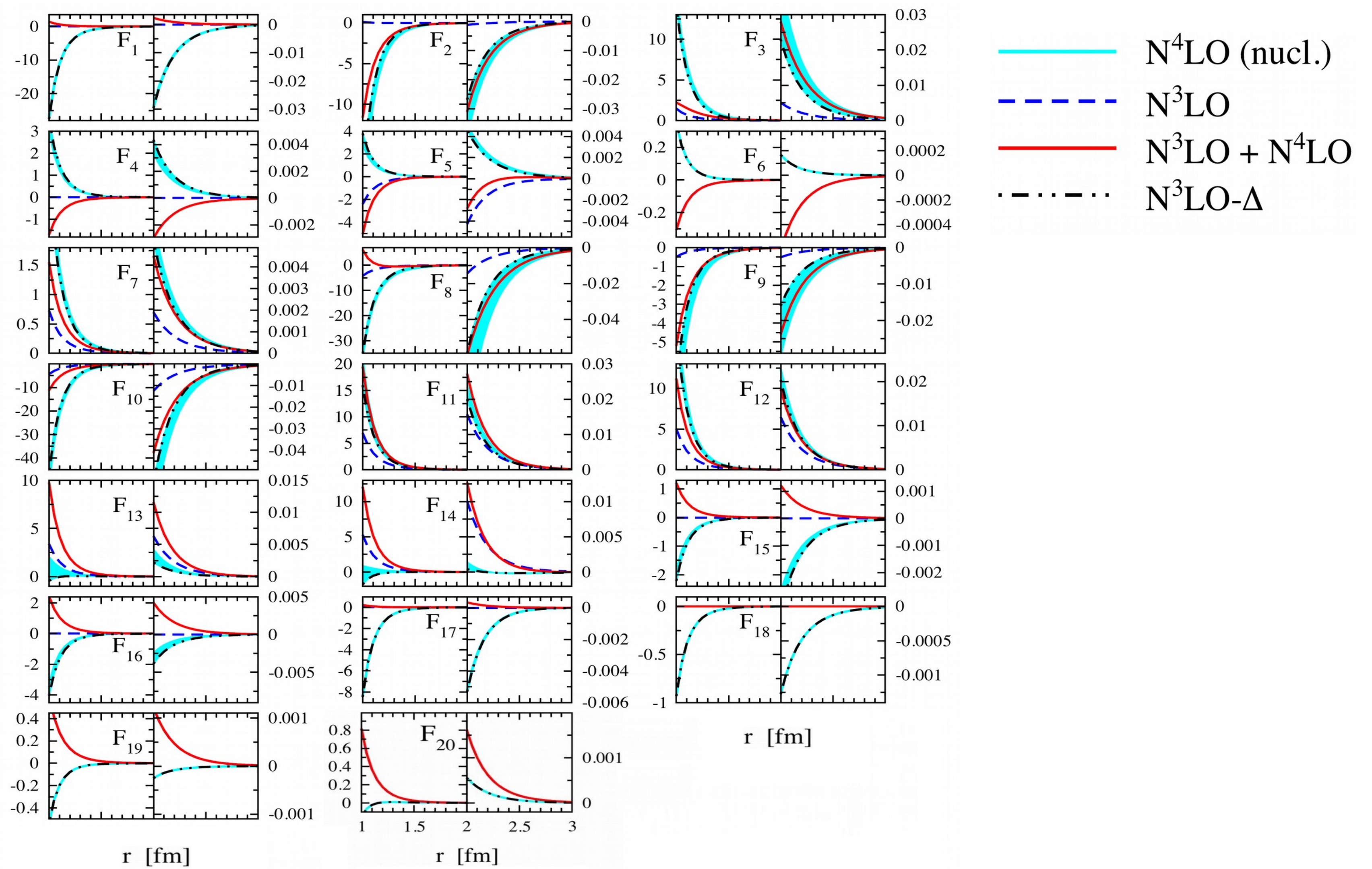


Bands indicate physics not described by explicit Δ–contributions

➔ Dominant effects come from N³LO-Δ/N⁴LO

➔ The largest N⁴LO contribution is saturated by Δ

Ring-topology 3NF in Δ–full and Δ–less approach (preliminary)



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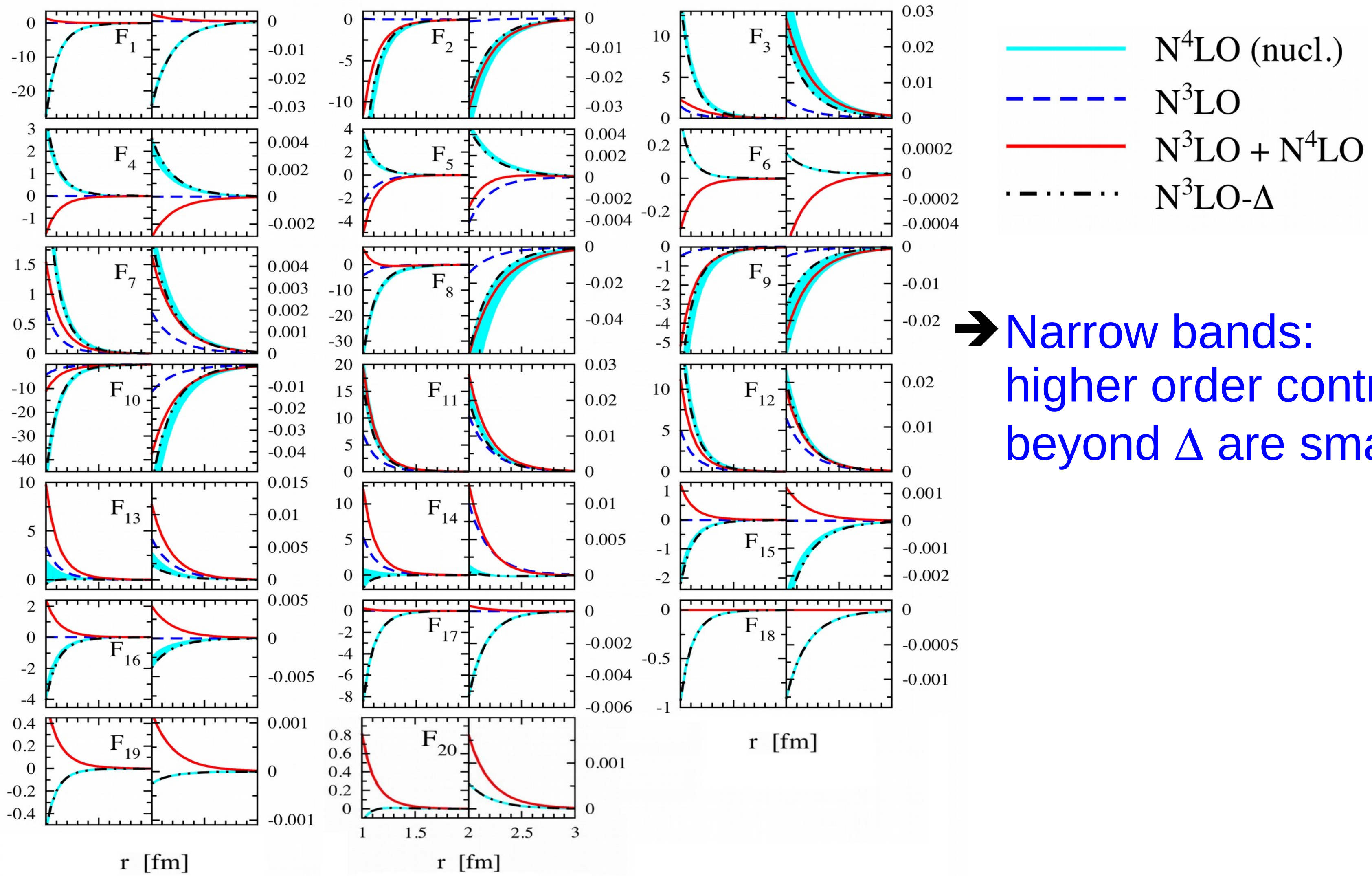
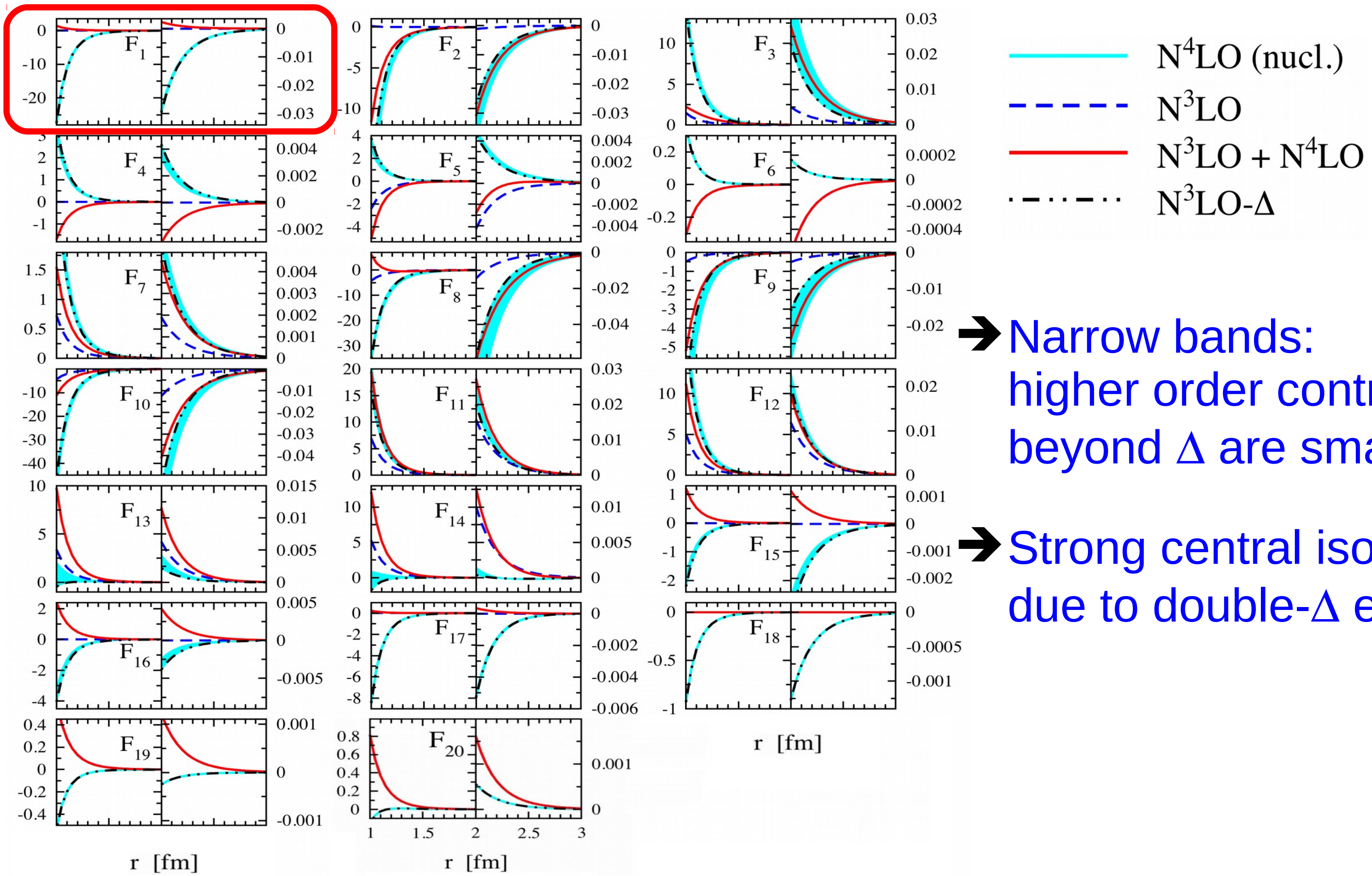


➔ Narrow bands: higher order contributions beyond Δ are small

Ring-topology 3NF in Δ–full and Δ–less approach (preliminary)



- ➔ Narrow bands: higher order contributions beyond Δ are small
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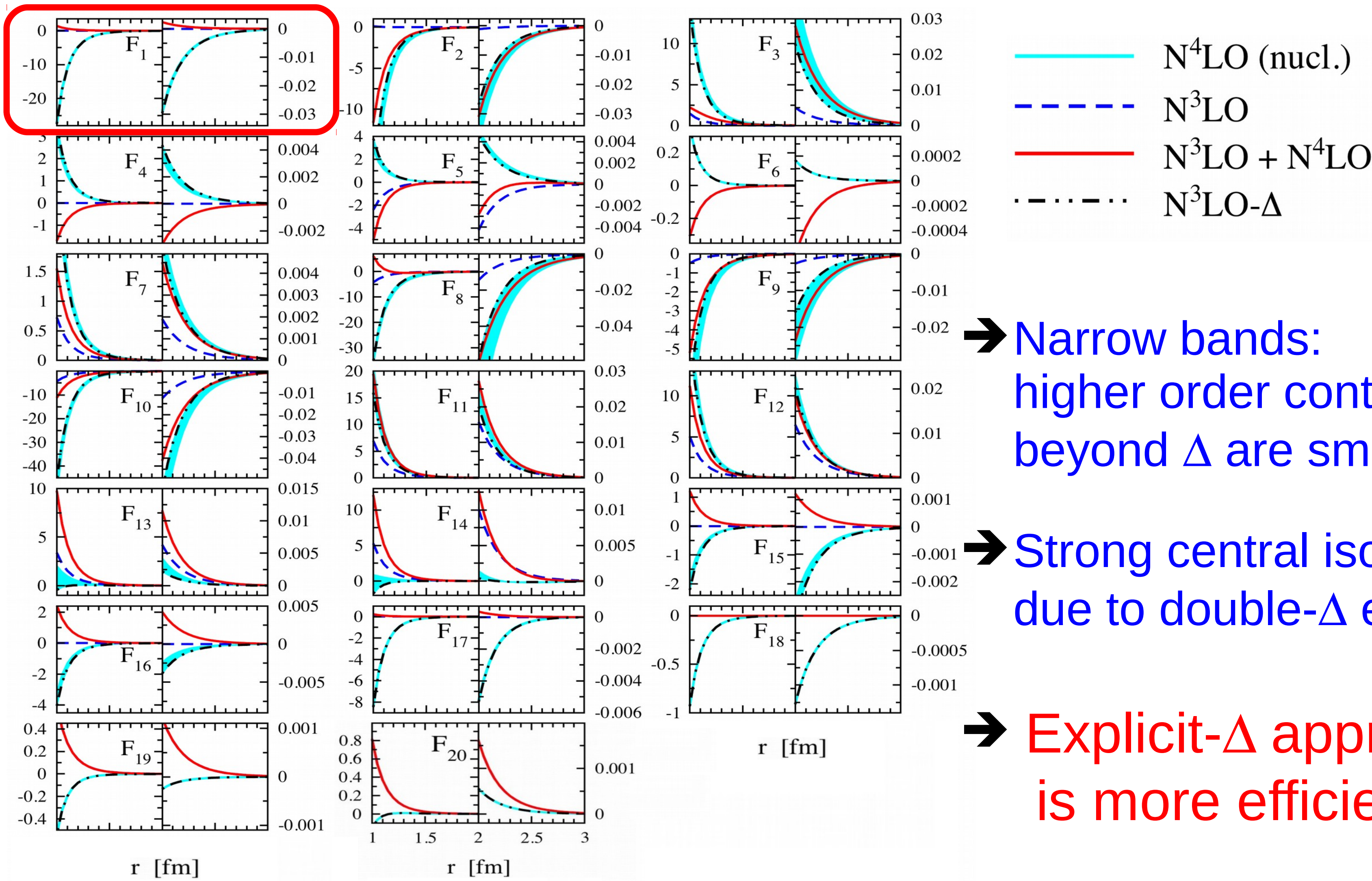


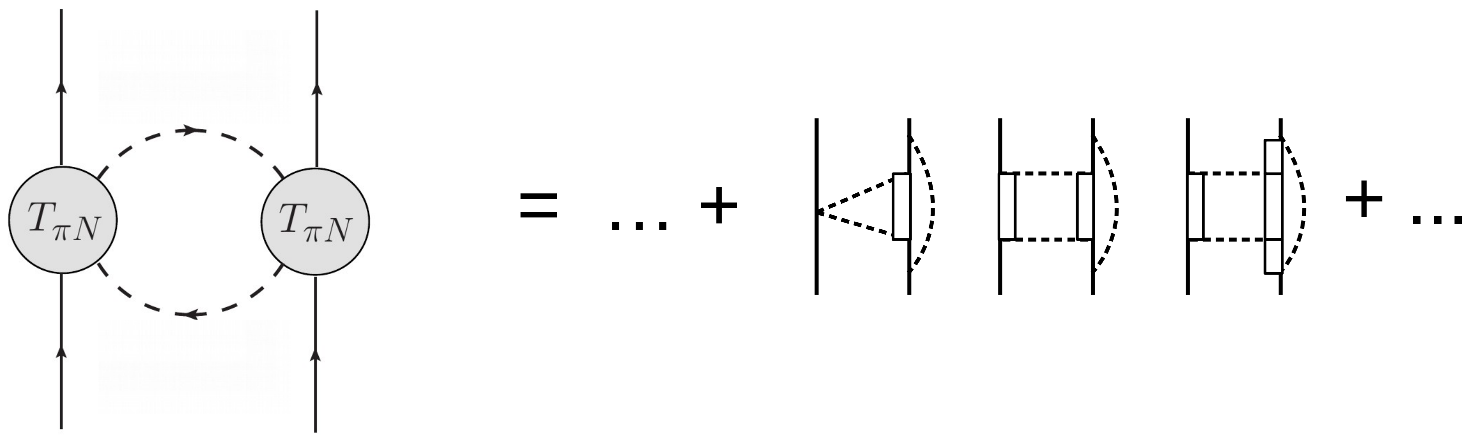
➔ Narrow bands: higher order contributions beyond Δ are small

➔ Strong central isoscalar 3NF due to double-Δ excitation

➔ Explicit-Δ approach is more efficient !

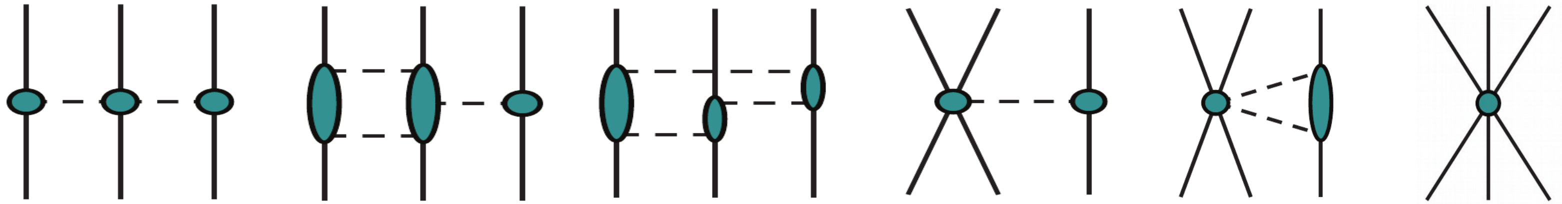
πN input for 2-Nucleon Forces

➔ 2-pion exchange contributions



πN input for 3-Nucleon Forces

- ➔ Longest-range contributions
- ➔ Intermediate-range contributions
- ➔ Short-range contributions



2π–exchange   2π–1π–exchange   ring

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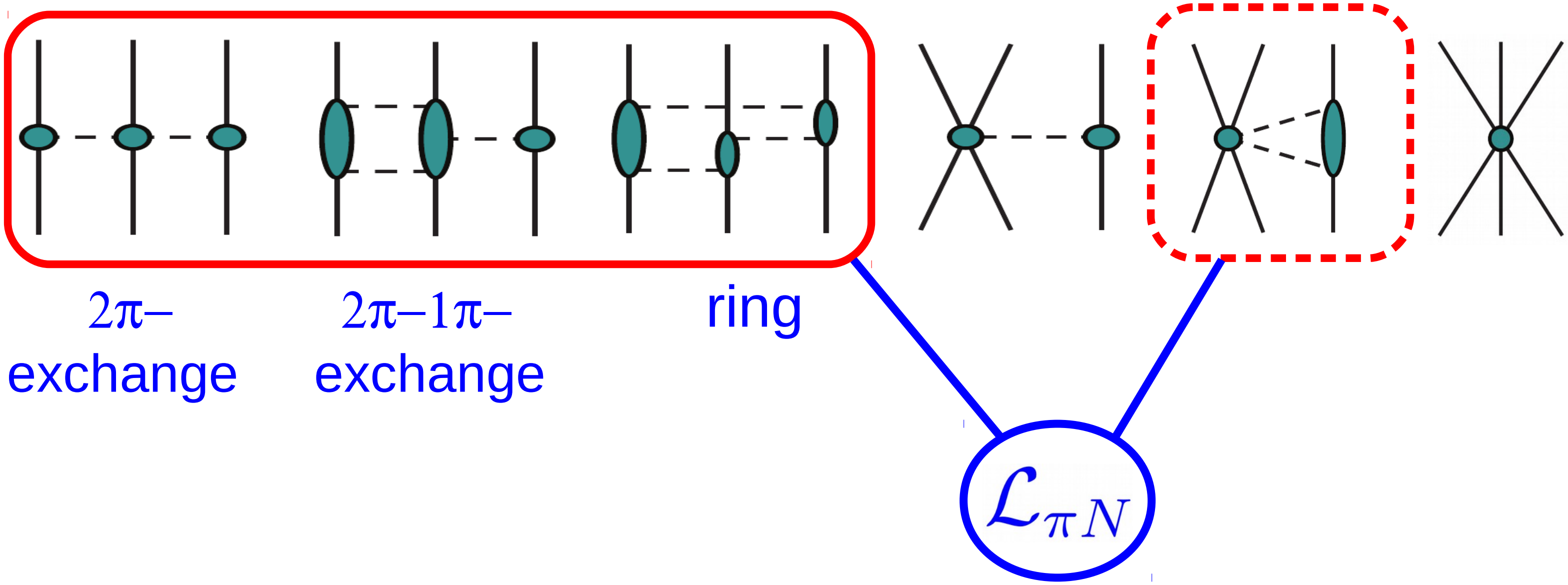
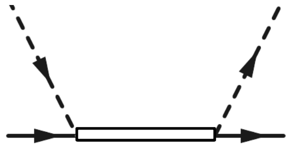


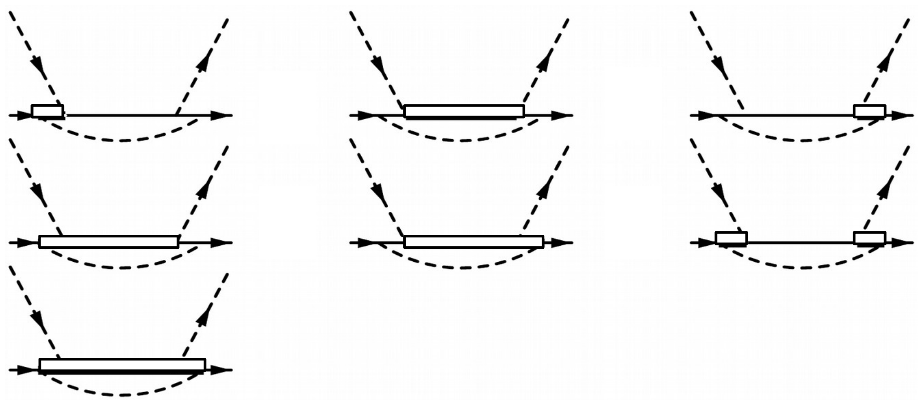
πN scattering up to ε^4

Siemens et al. In preparation

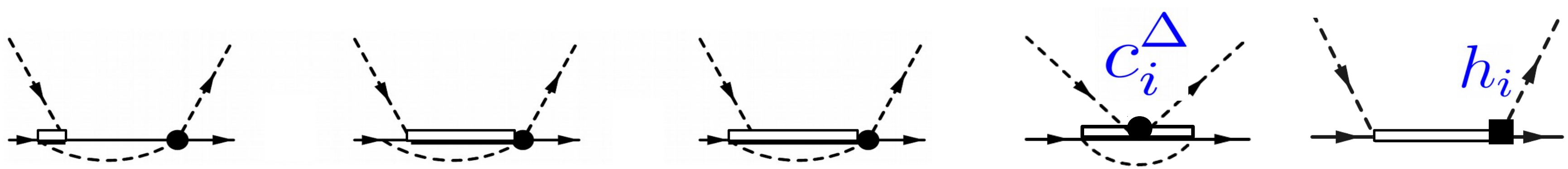
ε^1



ε^3



ε^4



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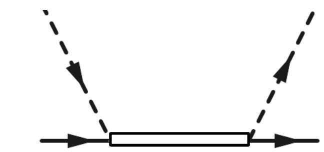
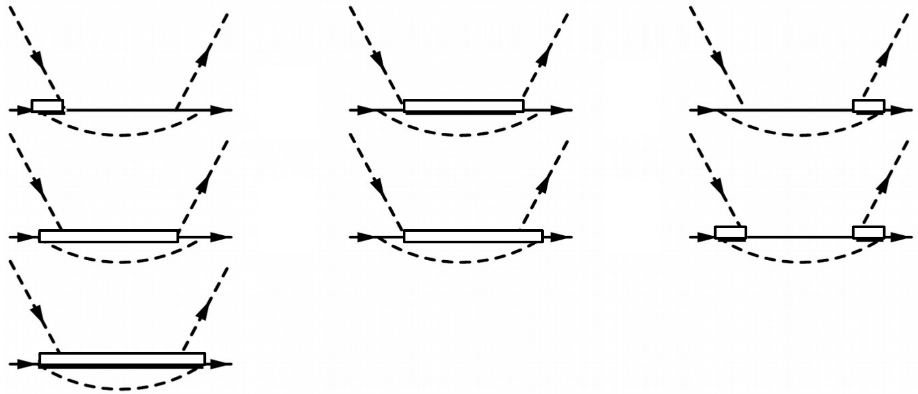
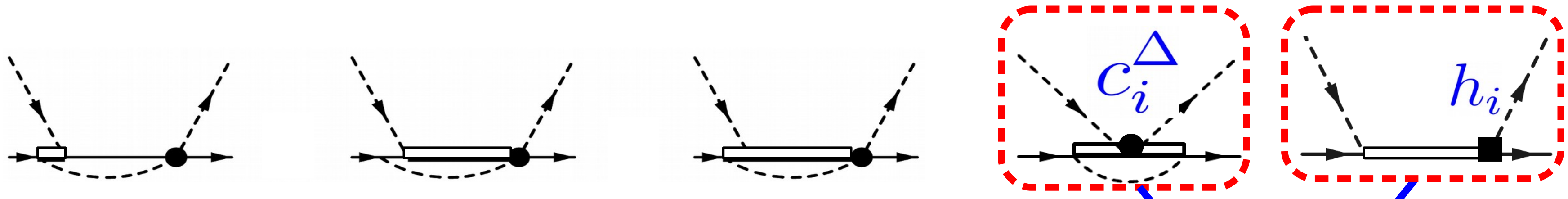


ε^3



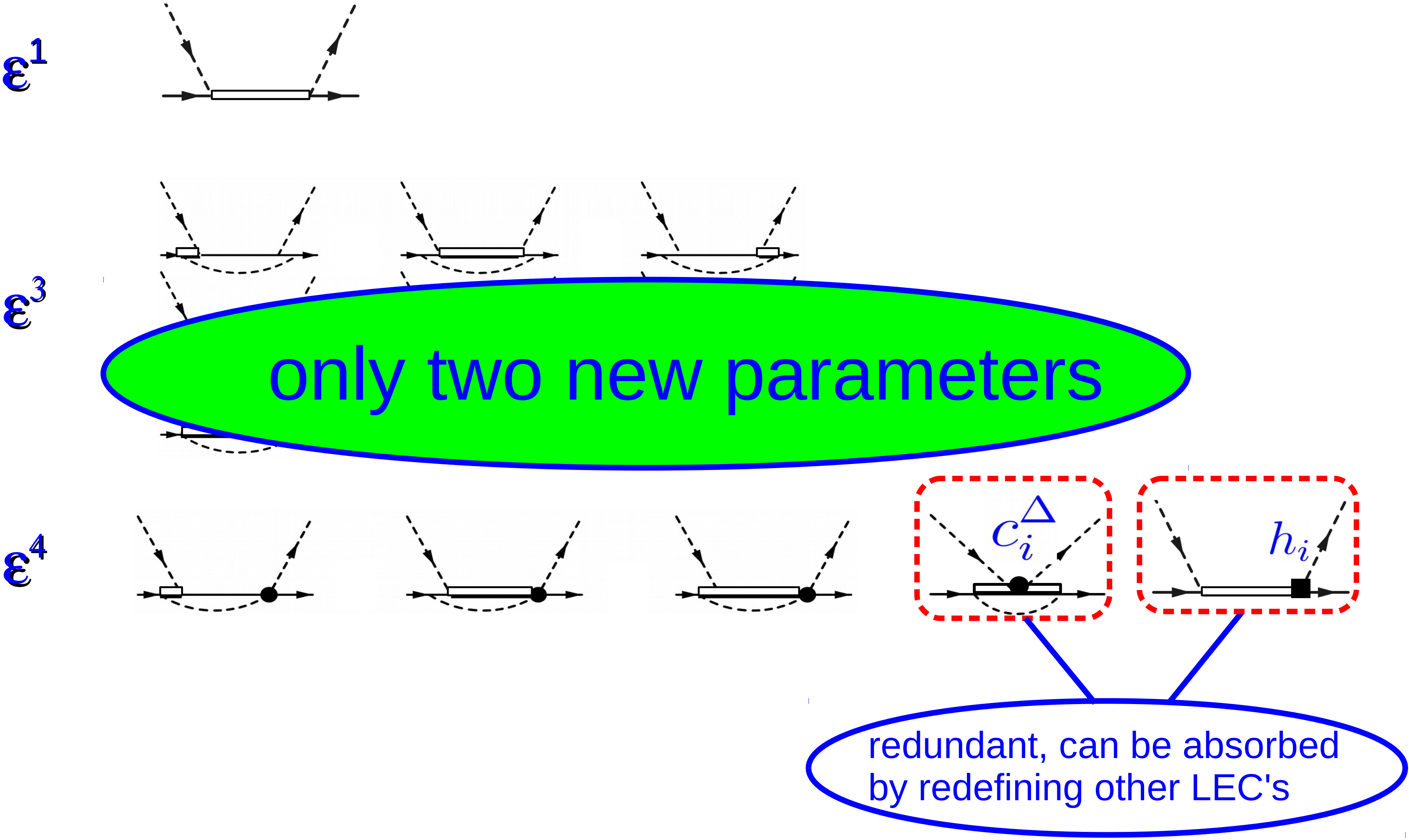
ε^4



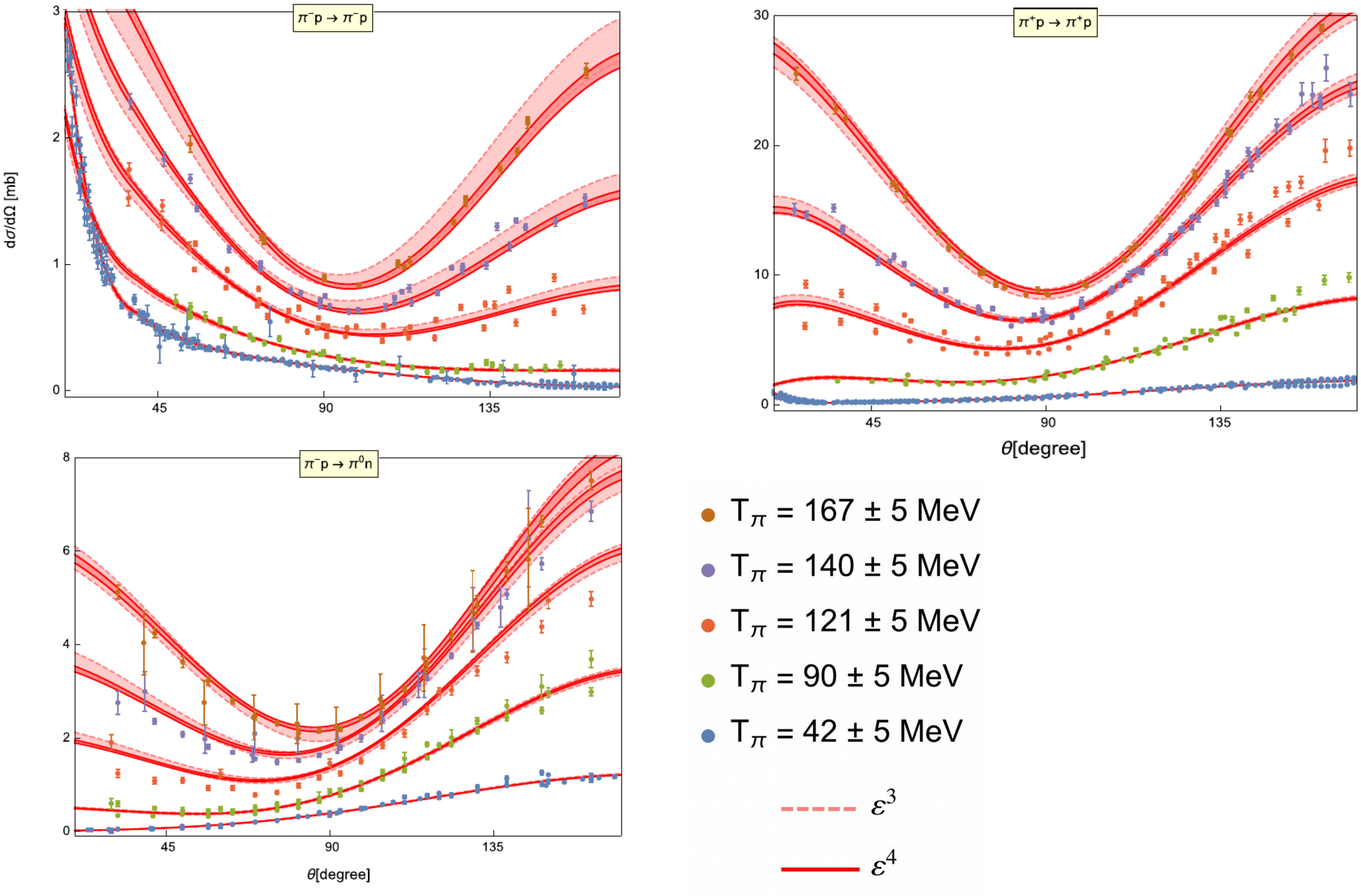
redundant, can be absorbed by redefining other LEC's

πN scattering up to ε^4

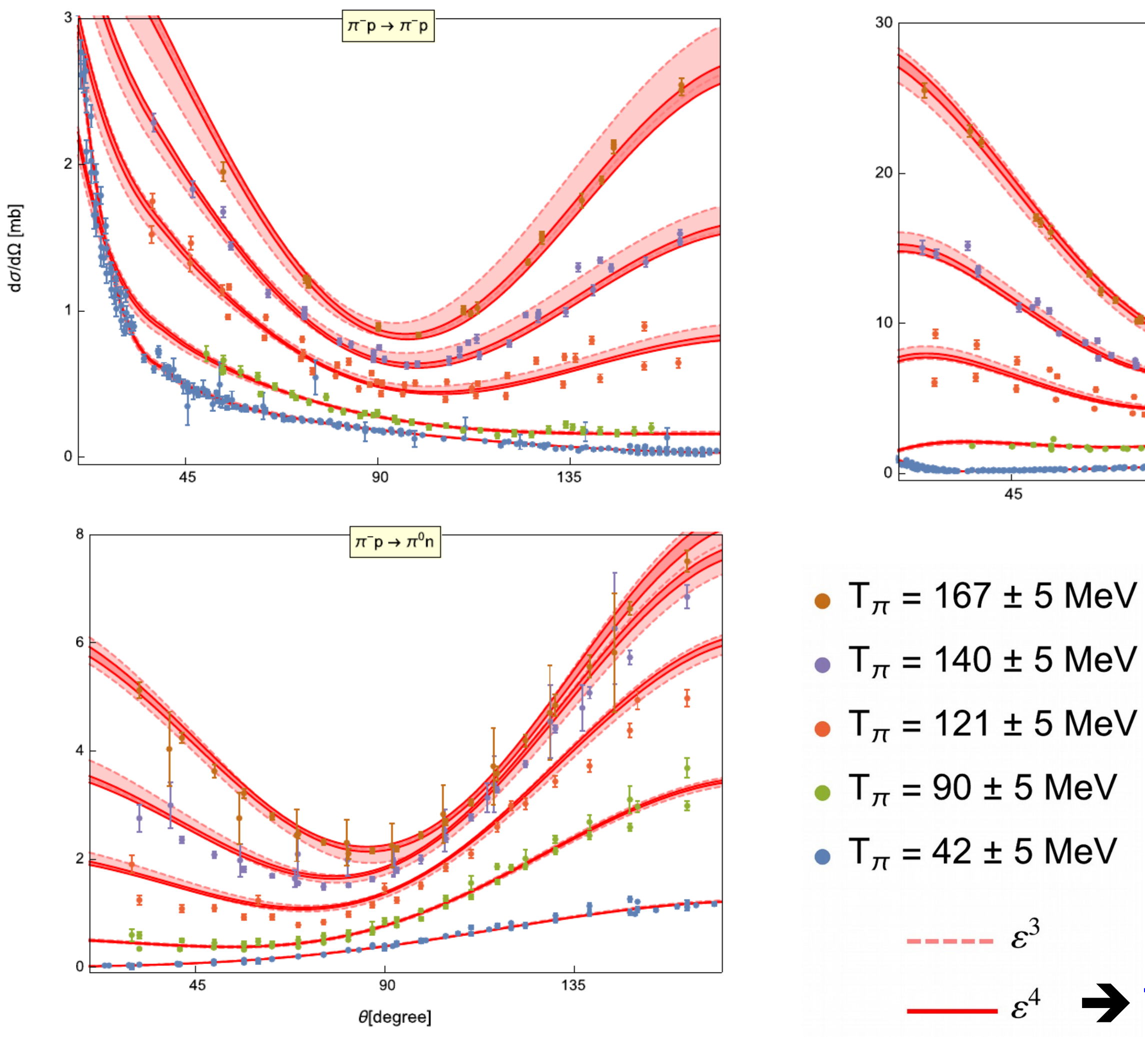
Siemens et al. In preparation



πN differential cross section



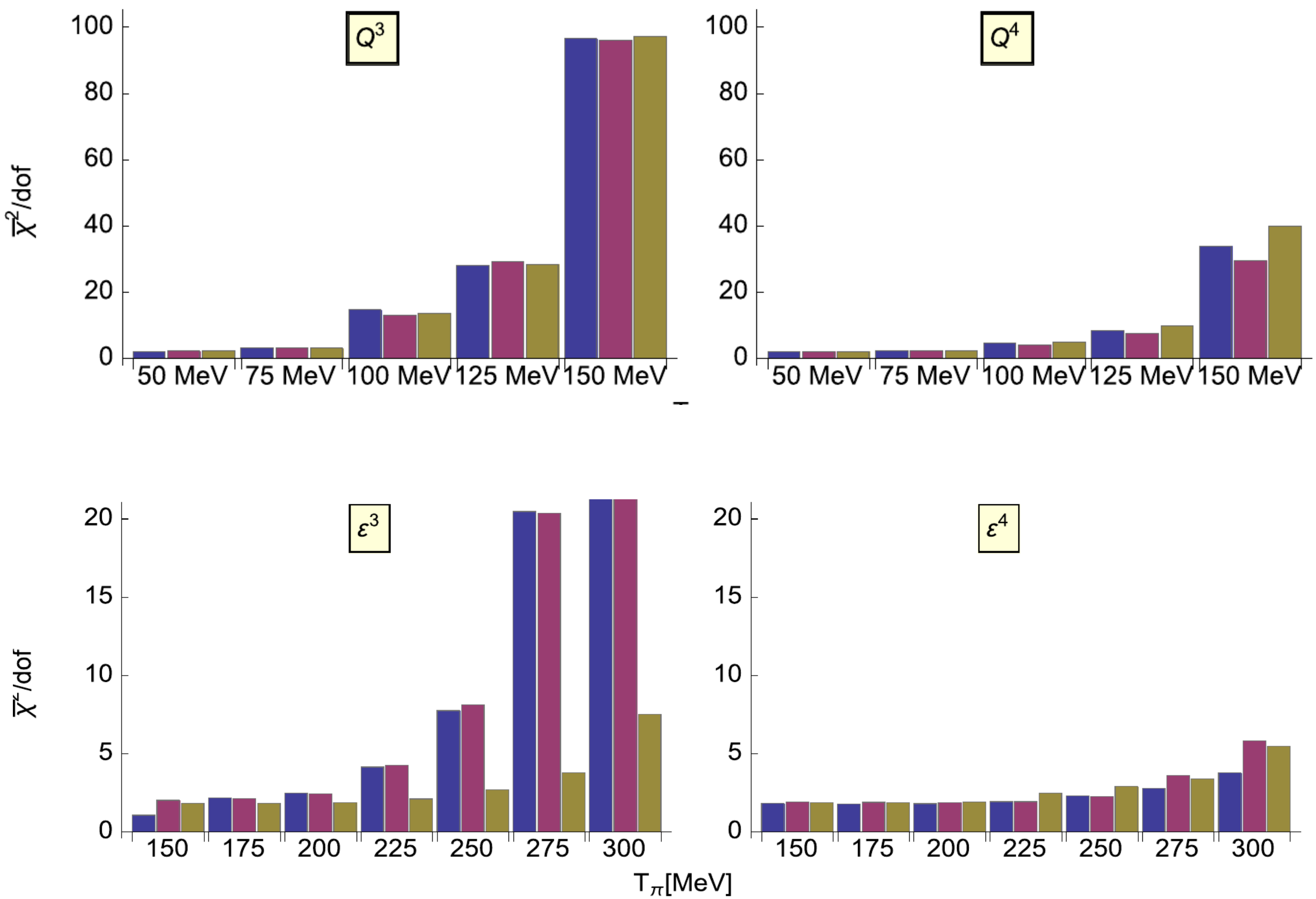
πN differential cross section



➔ Theoretical error-bands are narrower

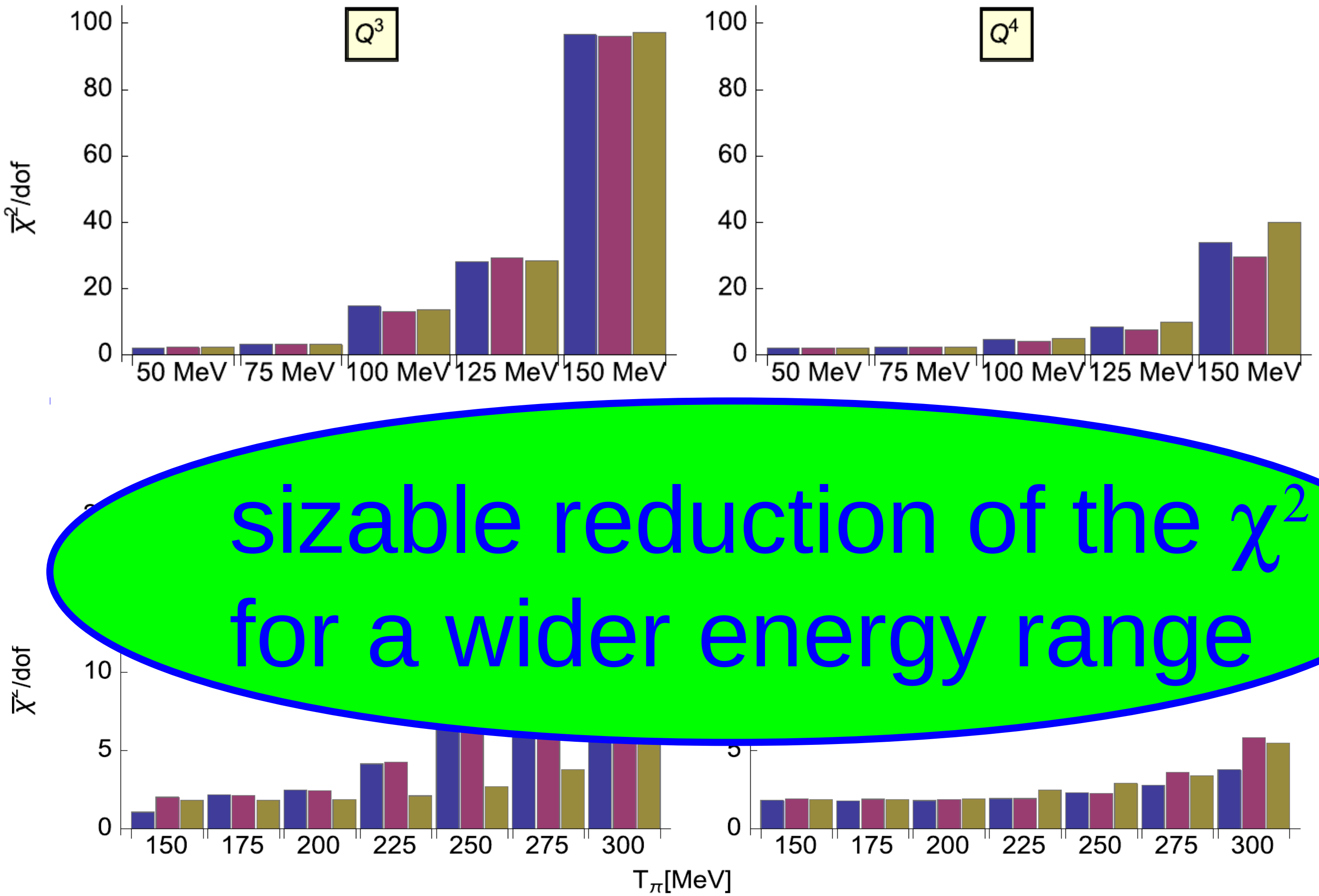
Quality of the fit to πN data
in the Δ–less and Δ–full χPT(without theoretical errors)

HB-NN HB-πN covariant



Quality of the fit to πN data in the Δ–less and Δ–full χPT(without theoretical errors)

HB-NN HB-πN covariant



sizable reduction of the χ^2 for a wider energy range

Summary

- Preliminary results for Δ-full chiral 2-nucleon and 3-nucleon forces at N^3LO are presented
- 2-nucleon forces (peripheral phases): significant improvement compared to the Δ-less case
- 3-nucleon forces: indication of a better convergence; sizable Δ-contributions missing in Δ-less N^4LO 3NF ~$O(1/\Delta^2)$
- New results for πN scattering at order ϵ^4: much better fit to data

Outlook

- Completing construction of Δ-full chiral 2N and 3N forces at N^3LO and moving forward to even more precise nuclear forces.