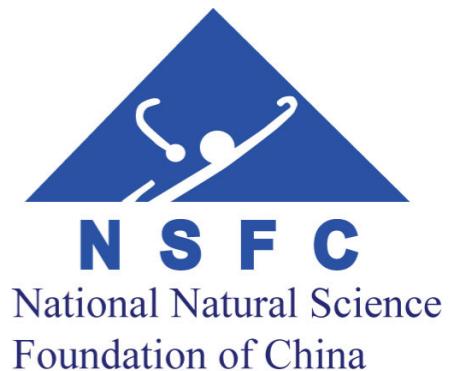


Toward RG invariant χ nuclear forces

- New ideas about 1S_0
- Perturbative NN in high partial waves

Bingwei Long
Sichuan University



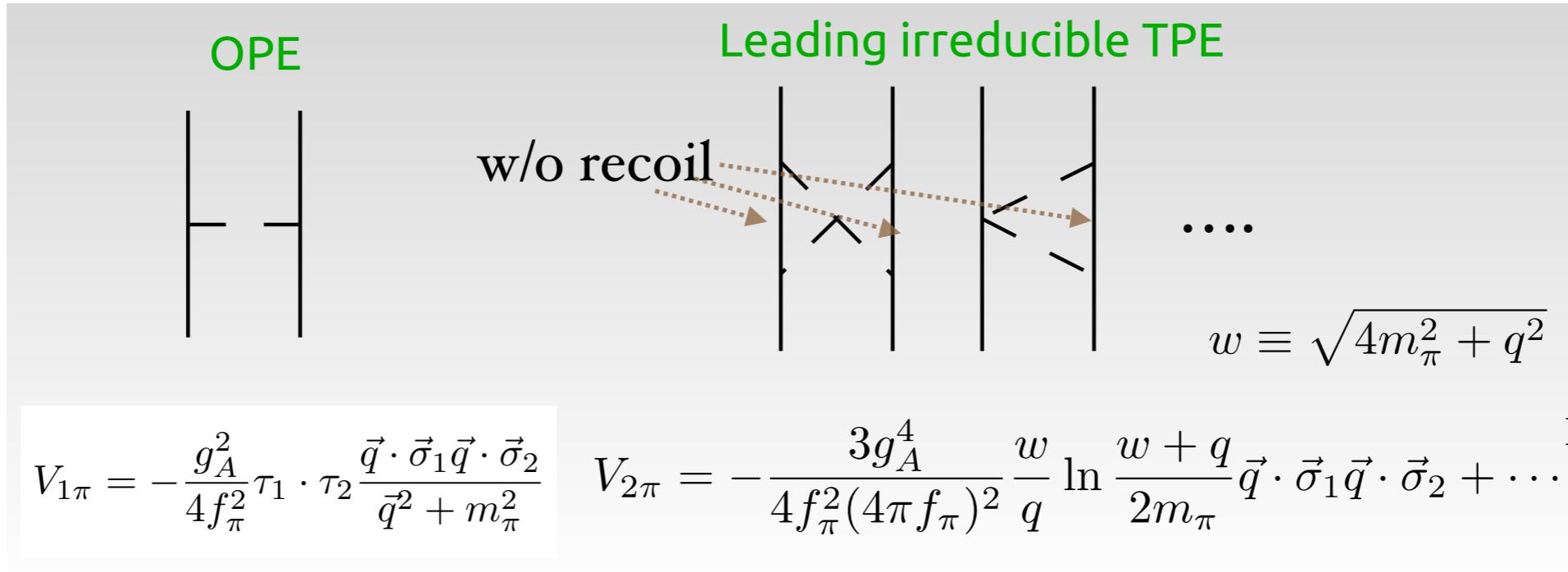
To promote, or not to promote ?

Building chiral EFT force that

- satisfies renormalization group inv. (cutoff independence)
- shows order-by-order convergence
- shows good agreement w/ PWA (by eyeballing)
- passes other consistency checks

Irreducible pion exchanges

- Power counting for pion-exchanges potentials follows standard ChPT



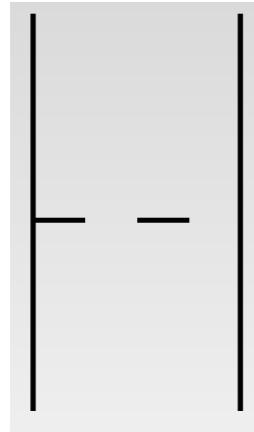
non-polynomials follow naïve dimensional analysis:

$$\frac{V_{2\pi}}{V_{1\pi}} \sim \frac{Q^2}{(4\pi f_\pi)^2} \mathcal{F}\left(\frac{Q}{m_\pi}\right)$$

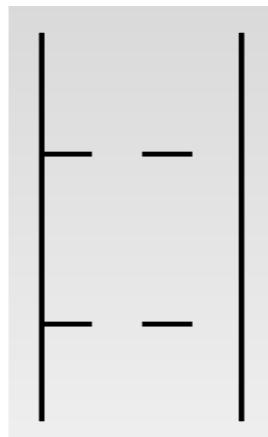
Weinberg's prescription: C.T. follow NDA (just like primordial C.T.)

An economical choice

Strength of OPE



$$\sim \frac{1}{f_\pi^2} \frac{Q^2}{m_\pi^2 + Q^2} \sim \frac{1}{f_\pi^2}$$



$$\sim \frac{1}{f_\pi^2} \frac{m_N Q}{4\pi f_\pi} \frac{1}{a_l f_\pi}$$

Suppression by
centrifugal barrier

Strength of OPE characterized by low-energy scale $a_l f_\pi$ (for small l)

- can influence C.T. through renormalization
- NDA no longer reliable

$$C_{3P0} \vec{p} \cdot \vec{p}' \sim \frac{Q^2}{m_{hi}^2} \quad \text{or} \quad C_{3P0} \vec{p} \cdot \vec{p}' \sim \frac{Q^2}{m_{lo}^2} \quad ?$$

Saga of 1S0

- ❖ First RG issue found with Weinberg PC (Kaplan et al. '96)

$$V_{1S0}^{(0)} = -\frac{g_A^2}{4f_\pi^2} \frac{m_\pi^2}{q^2 + m_\pi^2} + C_0 \quad C_q m_\pi^2 \propto \frac{m_\pi^2}{m_{lo}^2} \longrightarrow \text{LO}$$

$\mathcal{O}(Q)$

- ❖ NLO not vanishing

$$\text{LO cutoff error} = \mathcal{O}\left(\frac{k^2}{M_{lo}\Lambda}\right) \sim \mathcal{O}\left(\frac{Q}{\Lambda}\right)$$

$\mathcal{O}(Q^2)$
Larger than NNLO C.T. can compensate

$$C_2(p'^2 + p^2) \rightarrow \text{NLO} \quad (\text{BwL \& Yang '12})$$

Formal RG analysis: Birse '06, Pavon Valderrama '09

❖ Slow convergence

BwL & Yang '12

(Pavon Valderrama '09)

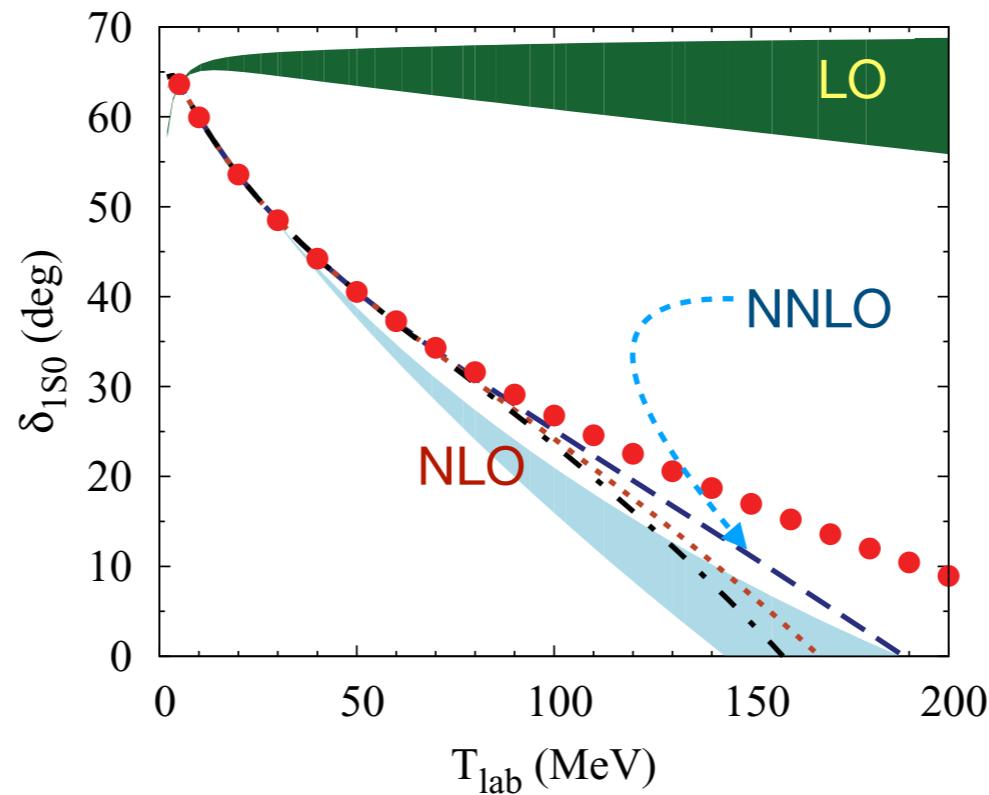


FIG. 2. (Color online) 1S_0 phase shifts as a function of laboratory energy. The red dots are from the Nijmegen PWA [35]. The dark green (light blue) band is the LO ($\mathcal{O}(Q)$) EFT result with $\Lambda = 0.5\text{--}2$ GeV. The dashed, dotted, and dot-dashed lines are $\mathcal{O}(Q^2)$ with $\Lambda = 0.5, 1$, and 2 GeV, respectively.

Additional low-energy scale “emerging” from underlying theory?

- ❖ Partially resumming energy (momentum) dep. contacts

Auxiliary 1S_0 dibaryon field (Kaplan '96; BwL '13)



$$\begin{aligned} \mathcal{L}_\phi = & \sigma \phi^\dagger \cdot \left(i \vec{\mathcal{D}}_0 + \frac{\vec{\mathcal{D}}^2}{4m_N} + \Delta \right) \phi + y (\phi_a^\dagger N^T P_a N + \text{H.c.}) \\ & + d_2 m_\pi^2 \left(\frac{1 - \pi^2/4f_\pi^2}{1 + \pi^2/4f_\pi^2} \right) \phi^\dagger \cdot \phi \end{aligned}$$

$$\mathcal{O}(1) \quad V^{(0)} = V_{Yukawa} + \frac{\sigma y^2}{E + \Delta} \quad \xrightarrow{\text{RG inv.}} \quad T_{1S0}^{(0)} = T_{Yukawa} + \frac{\chi^2(k; k)}{\frac{E + \Delta}{\sigma y^2} - I_k}$$

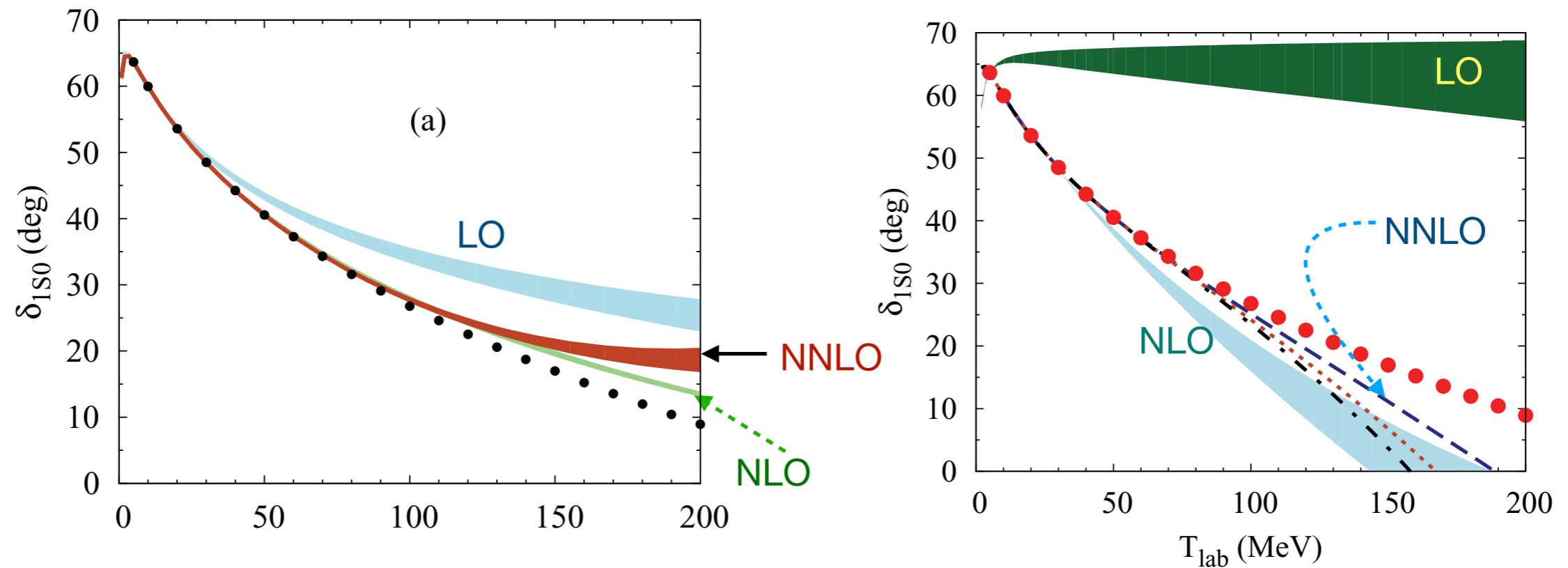
$\mathcal{O}(Q)$

C_0

$\mathcal{O}(Q^2)$

$C_2(p'^2 + p^2) + V_{2\pi}^{(0)}$

> perturbations !



- ❖ Improved convergence
- ❖ Resolved pion-mass dep. issue

Resum even more C.T.

$$\mathcal{O}(1) \quad V_{Yukawa} + \frac{\sigma y^2}{E + \Delta}$$

$$\mathcal{O}(Q) \quad C_0$$

$$\mathcal{O}(Q^2) \quad C_2(p'^2 + p^2) + V_{2\pi}^{(0)}$$

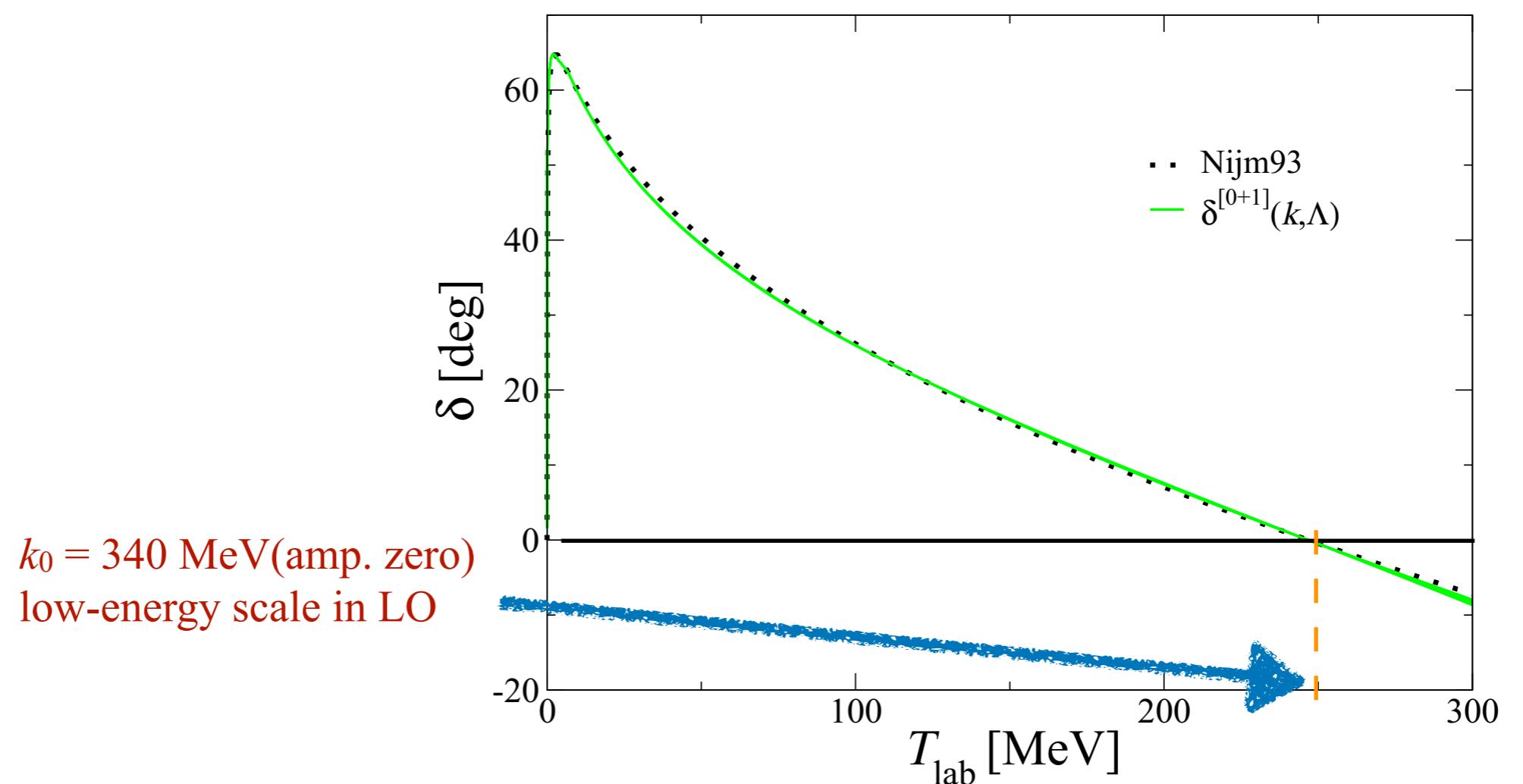
Sanchez et al. '17

$$C_0 + V_{Yukawa} + \frac{\sigma y^2}{E + \Delta}$$

$$C_2(p'^2 + p^2)$$

$$C_4 p'^2 p^2 + V_{2\pi}^{(0)}$$

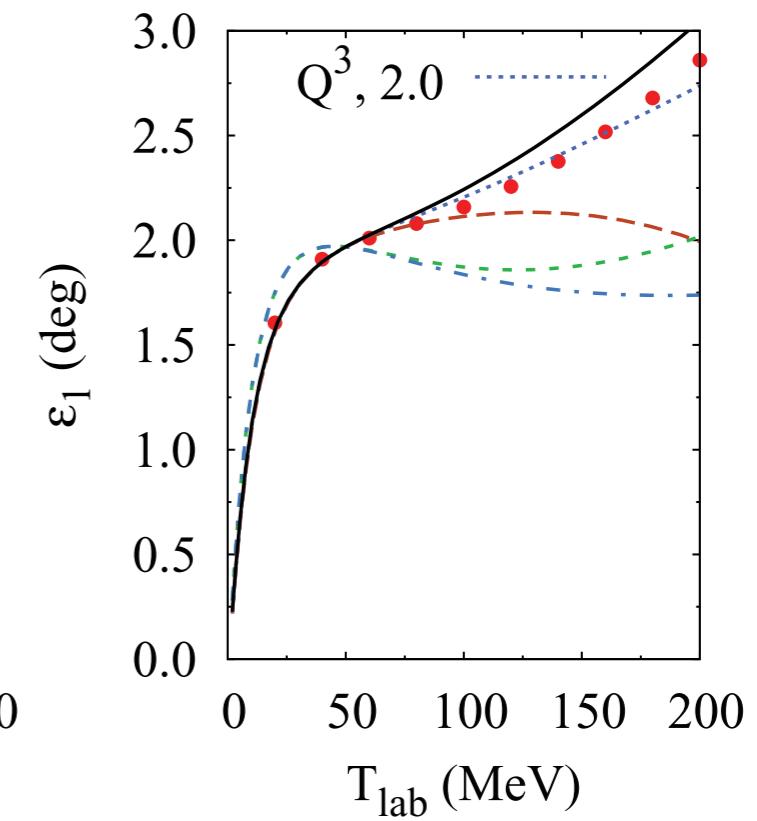
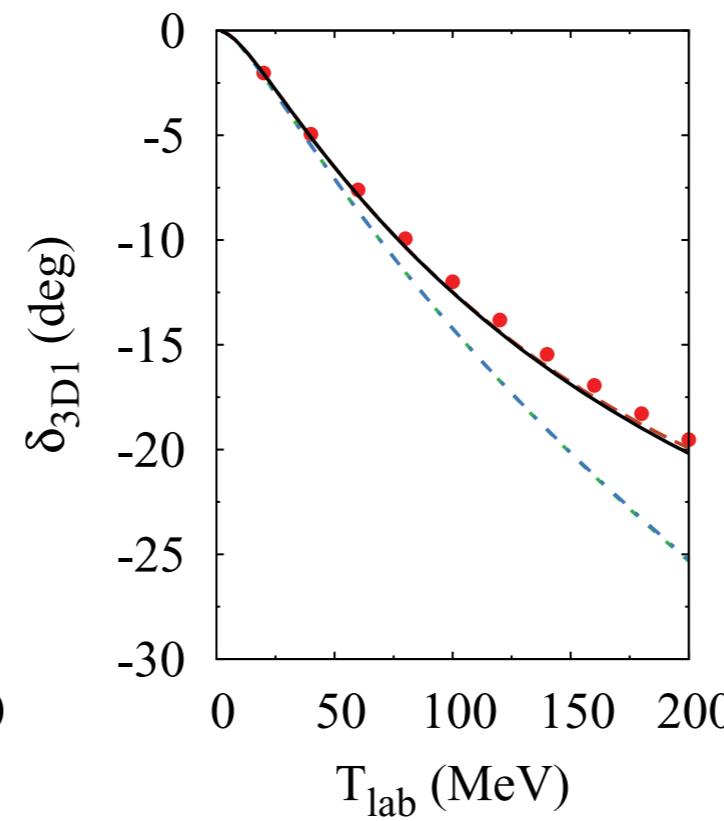
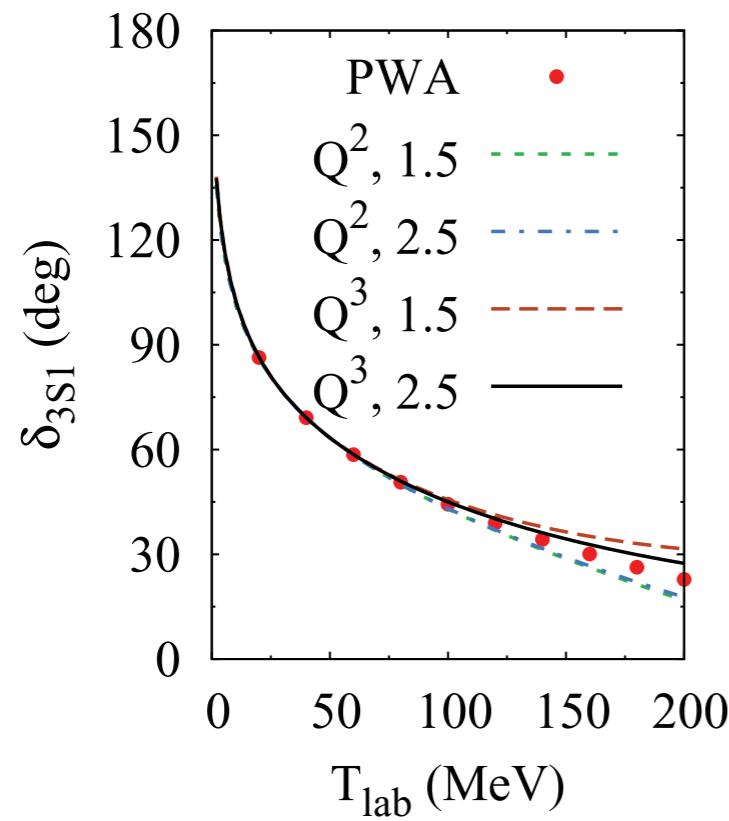
Still RG inv.



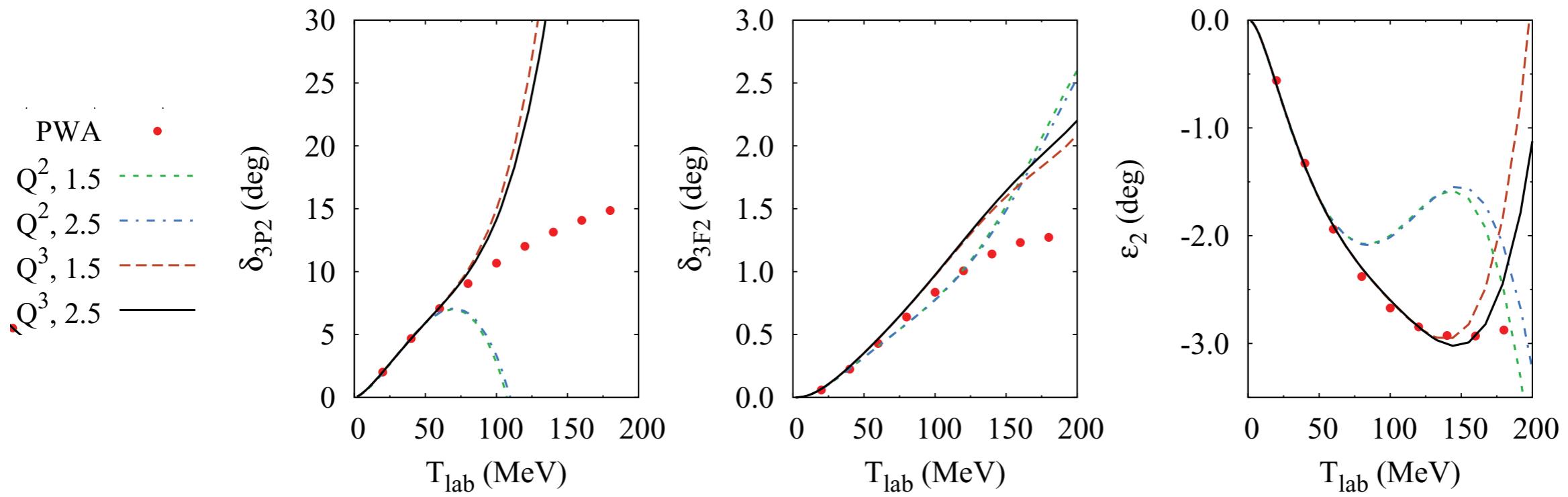
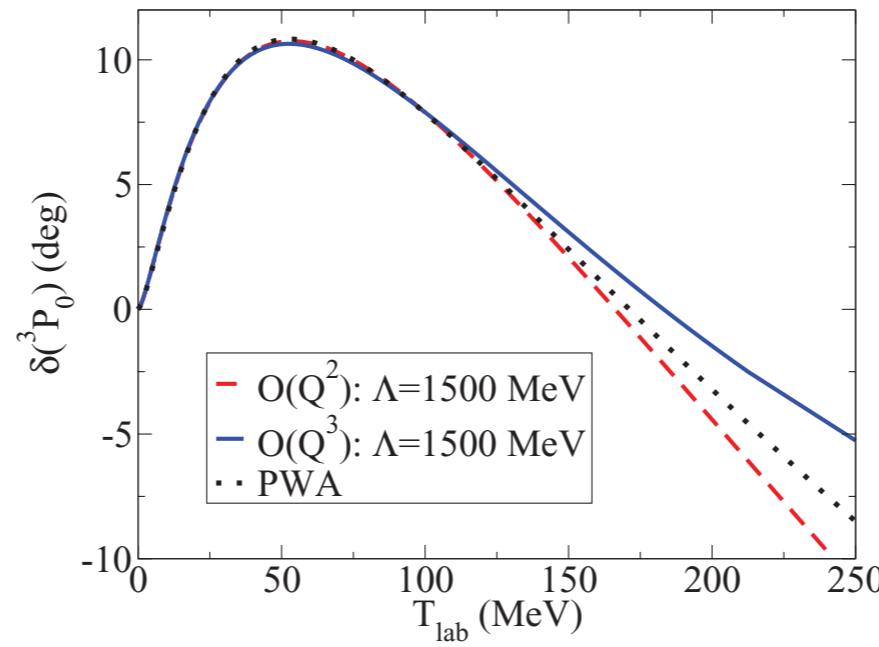
- No change to WPC in $^3\text{S}_1$ - $^3\text{D}_1$, subleading orders in pert.

BwL & Yang 'II

(Pavon Valderrama 'II)



- N.P. OPE, promote C.T.s from WPC by two orders in ${}^3\text{P}_0$, ${}^3\text{P}_2-{}^3\text{F}_2$



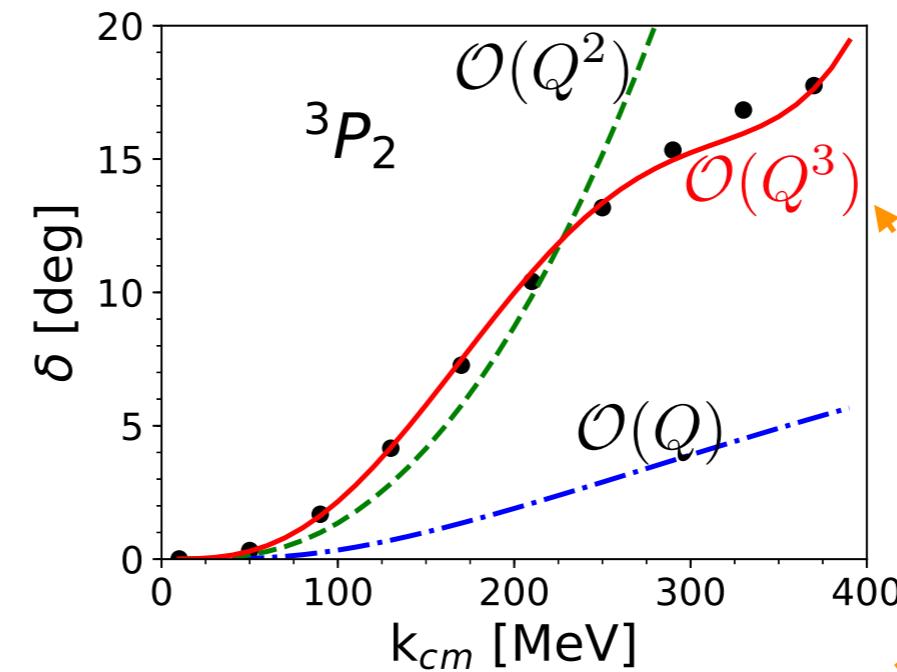
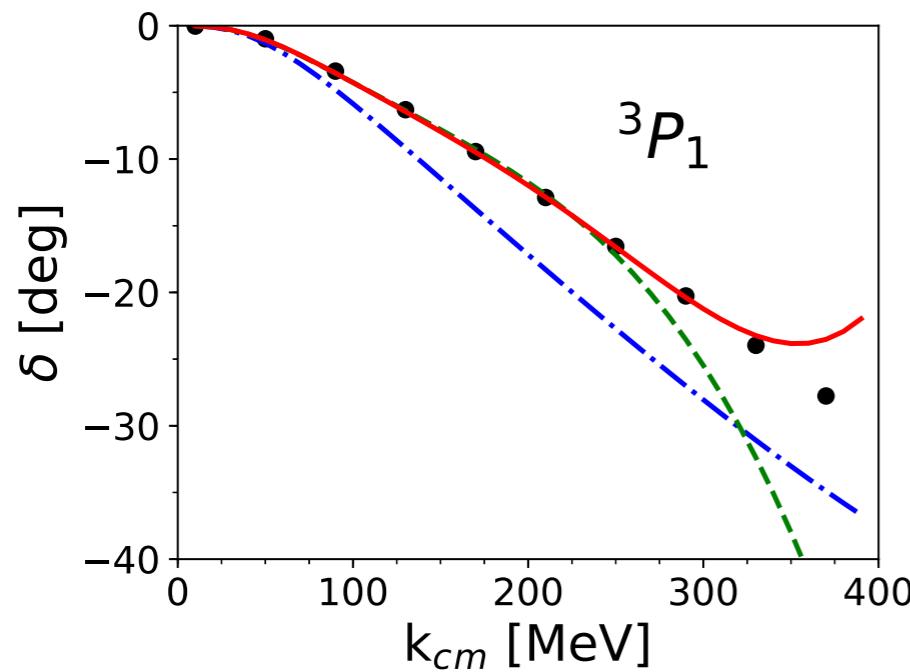
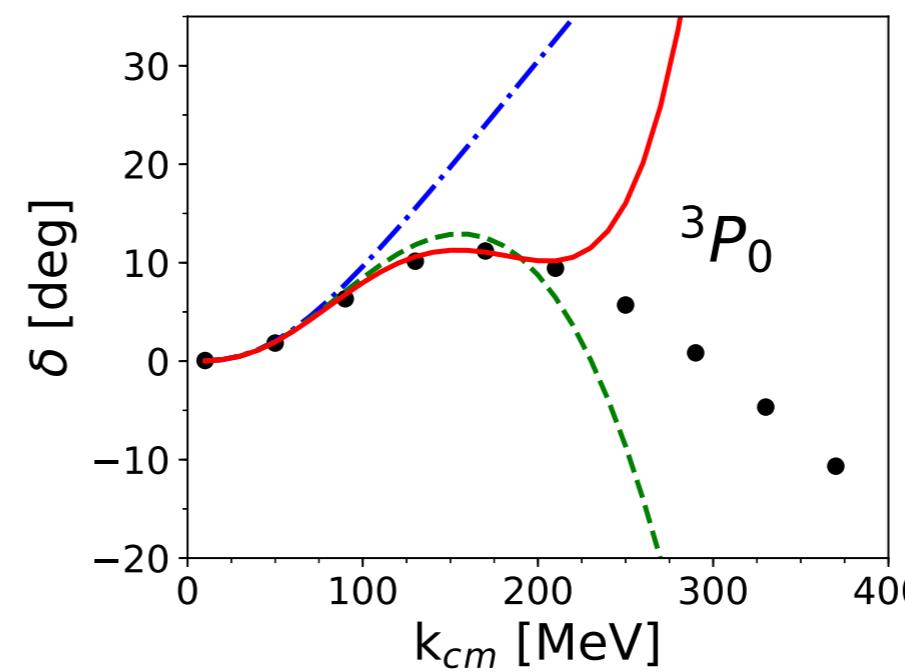
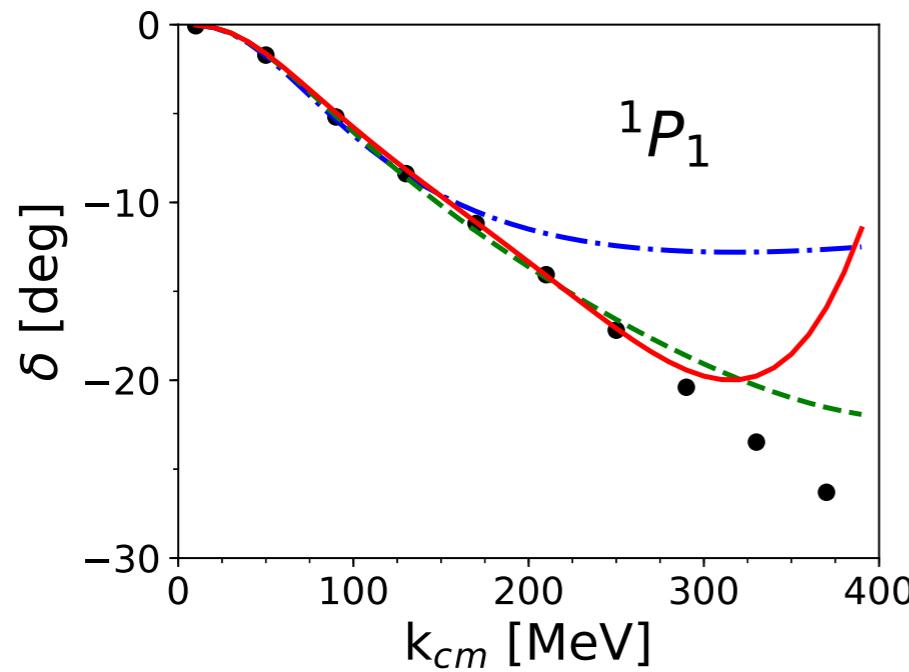
Perturbative NN

For L large enough, OPE becomes perturbative

		Amplitude
$\mathcal{O}(1)$	0	
$\mathcal{O}(Q)$	$V_{1\pi} \sim \frac{4\pi}{m_N} \frac{1}{M_{hi}}$	$\stackrel{=}{\equiv} V^{\text{NNLO}}$
$\mathcal{O}(Q^2)$	$V_{1\pi} G_0 V_{1\pi}$	$\boxed{V_{2\pi}^{(0)} - C_2 Q^2}$
$\mathcal{O}(Q^3)$	$V_{1\pi} G_0 V_{1\pi} G_0 V_{1\pi}$	$V_{1\pi} G_0 V^{\text{NNLO}} + V^{\text{NNLO}} G_0 V_{1\pi}$
$V_{2\pi}^{(0)}$	leading TPE	$V_{2\pi}^{(1)}$
$V_{2\pi}^{(1)}$	subleading TPE (w/ c_i 's)	$\boxed{C_4 Q^4}$

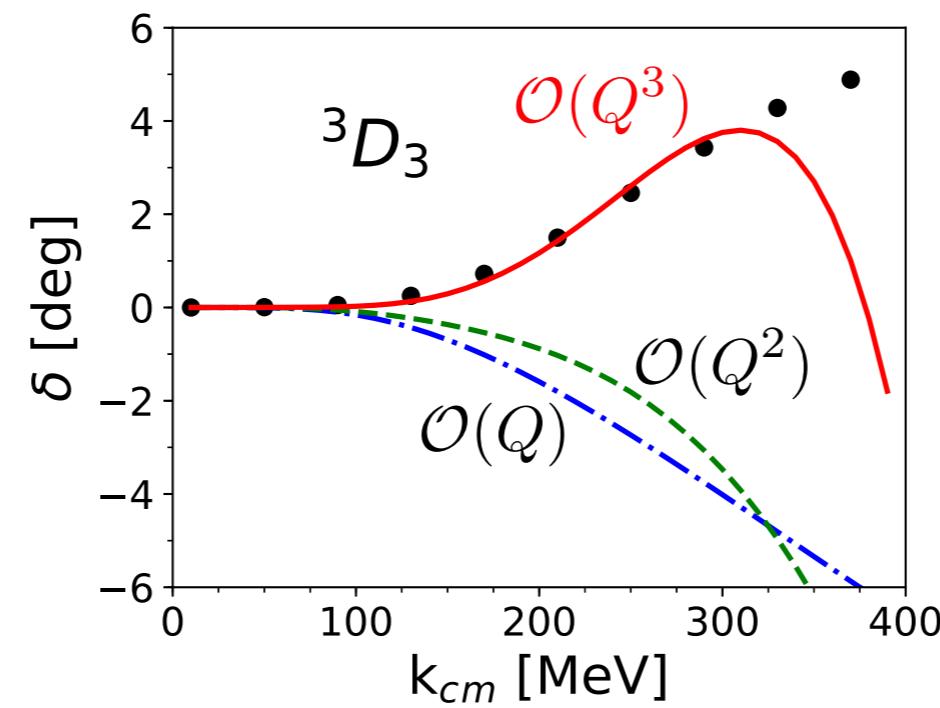
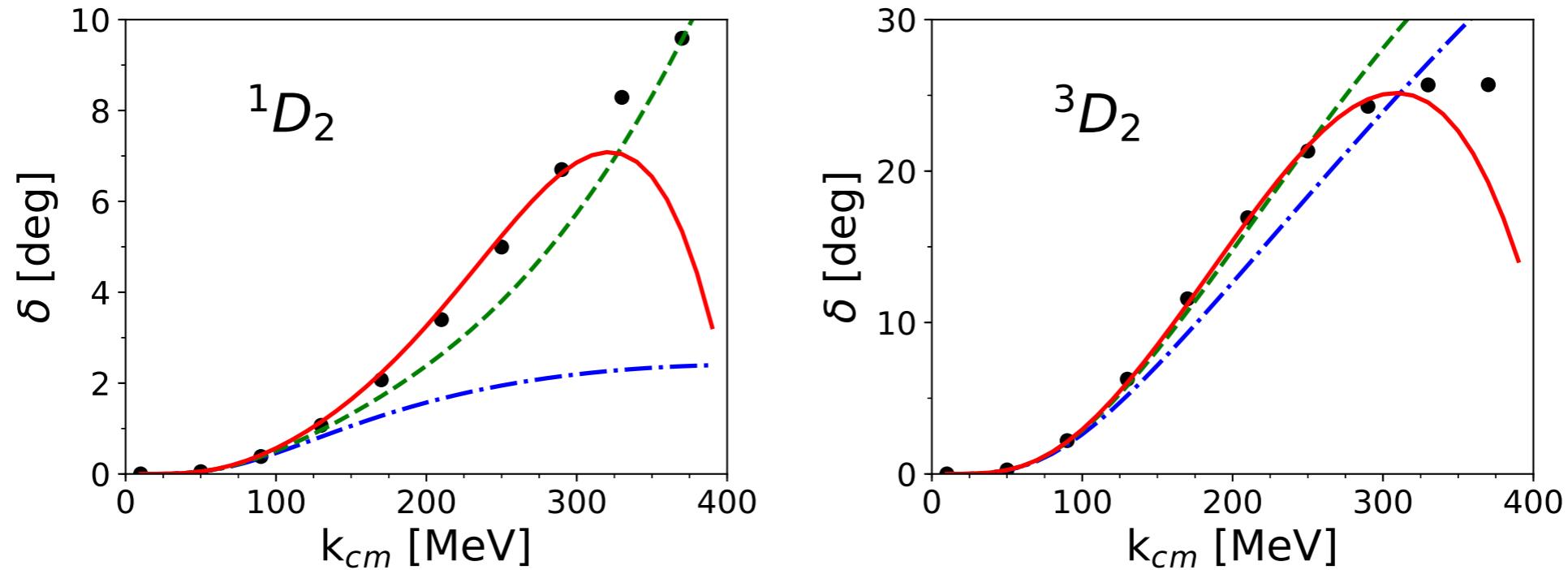
Delta-less

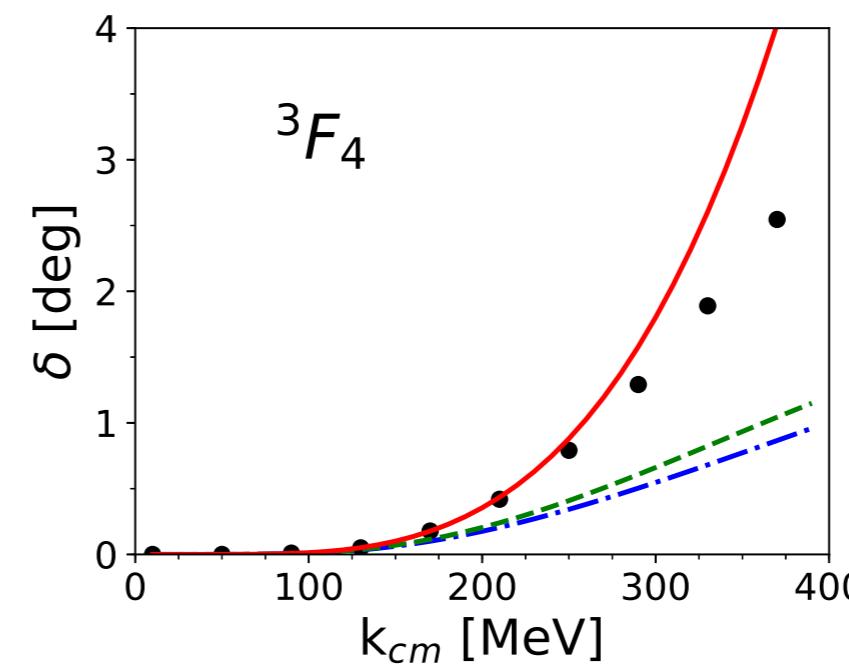
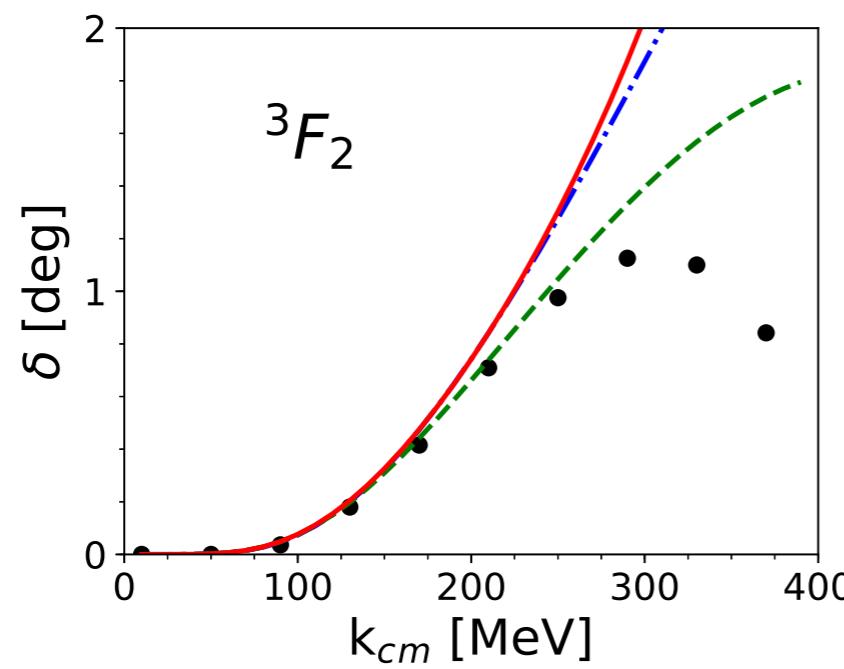
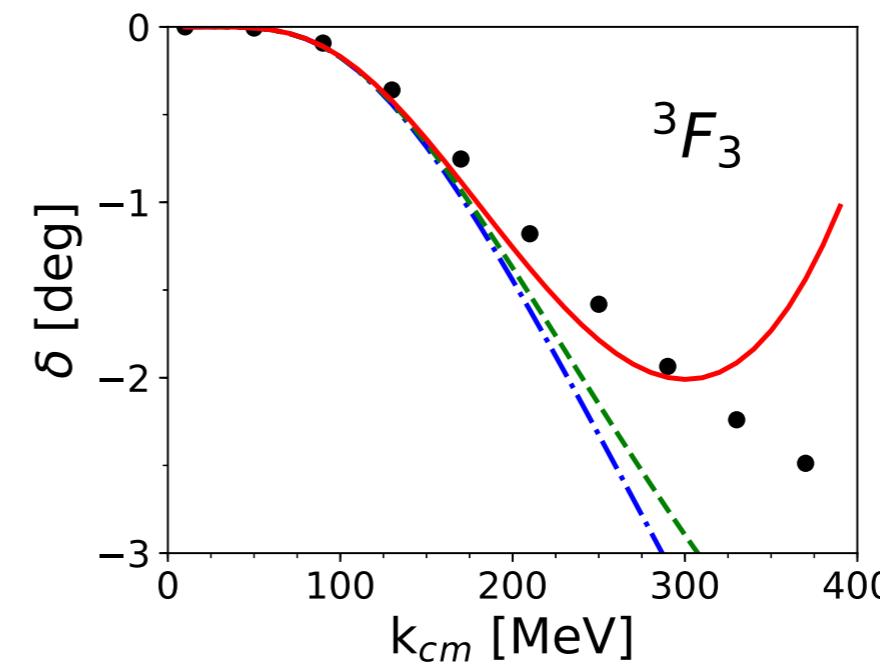
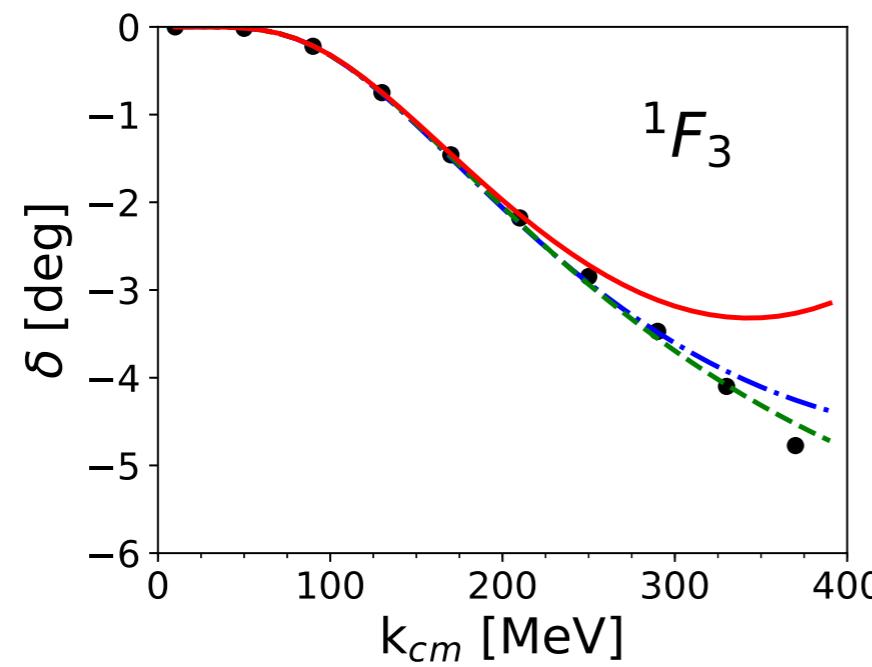
promoted by one
 order from WPC

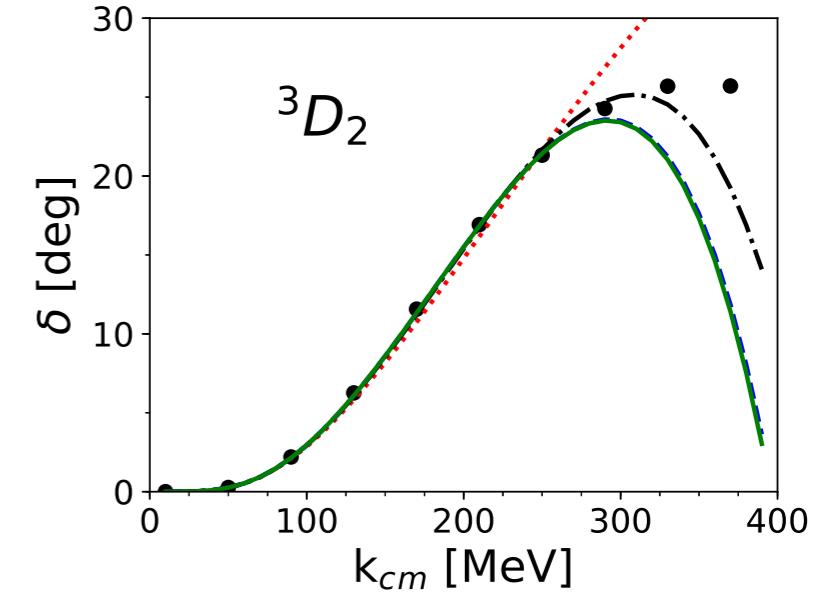
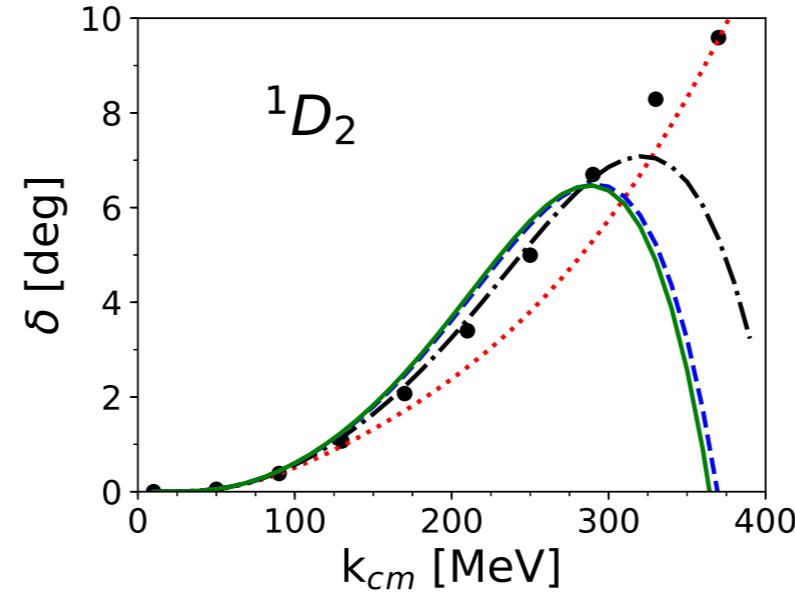
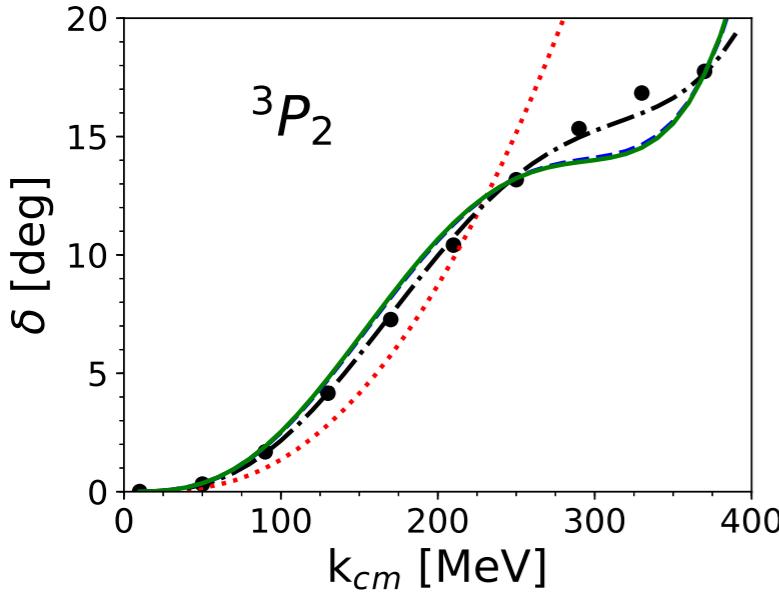
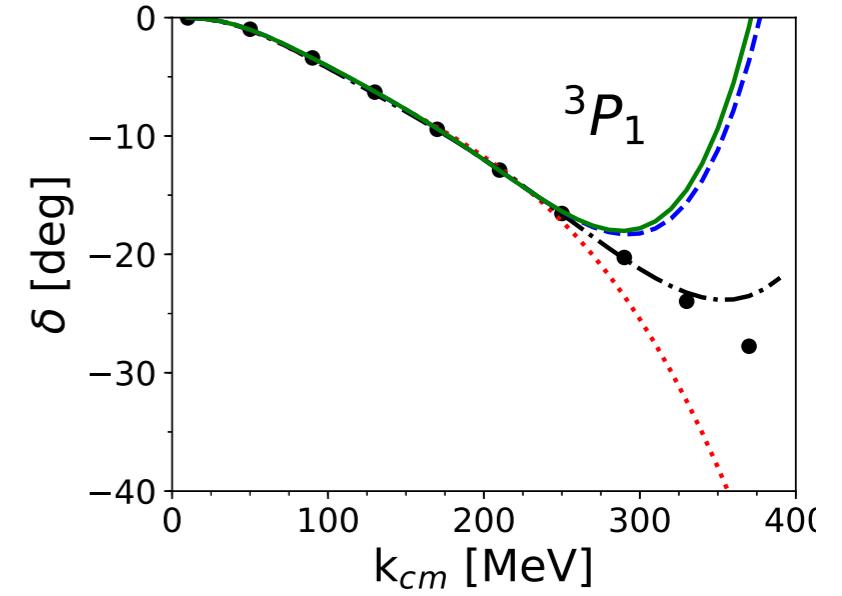
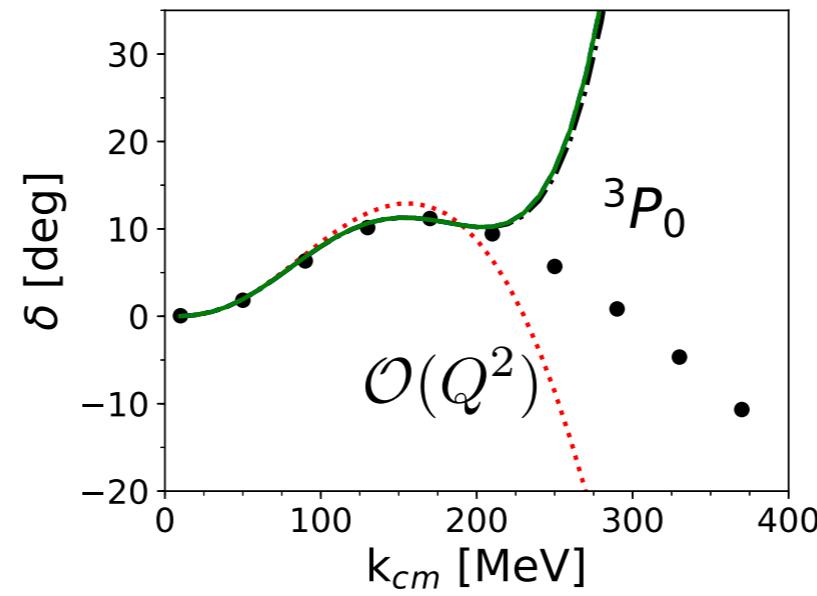
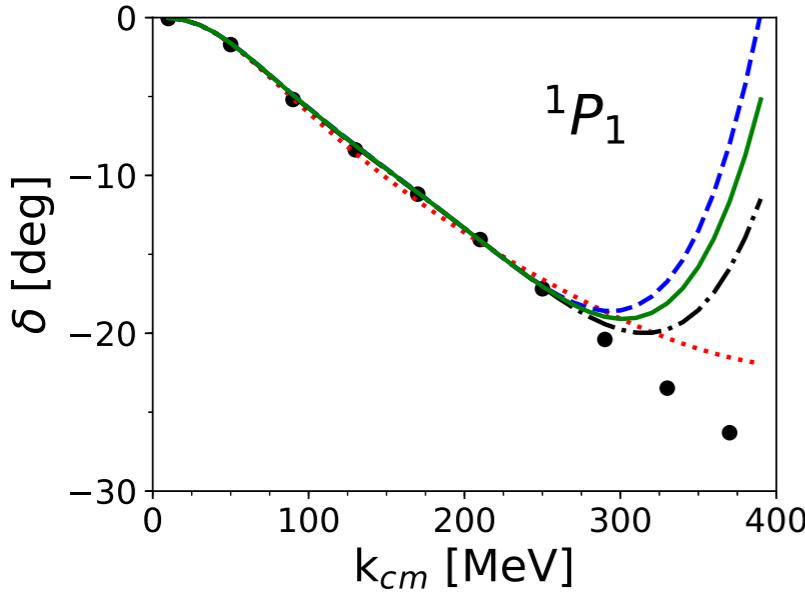


Hoefrichter et al. '15, '16

	NNLO	N ³ LO	N ⁴ LO
c_1	-0.74(2)	-1.07(2)	-1.10(3)
c_2		3.20(3)	3.57(4)
c_3	-3.61(5)	-5.32(5)	-5.54(6)
c_4	2.44(3)	3.56(3)	4.17(4)





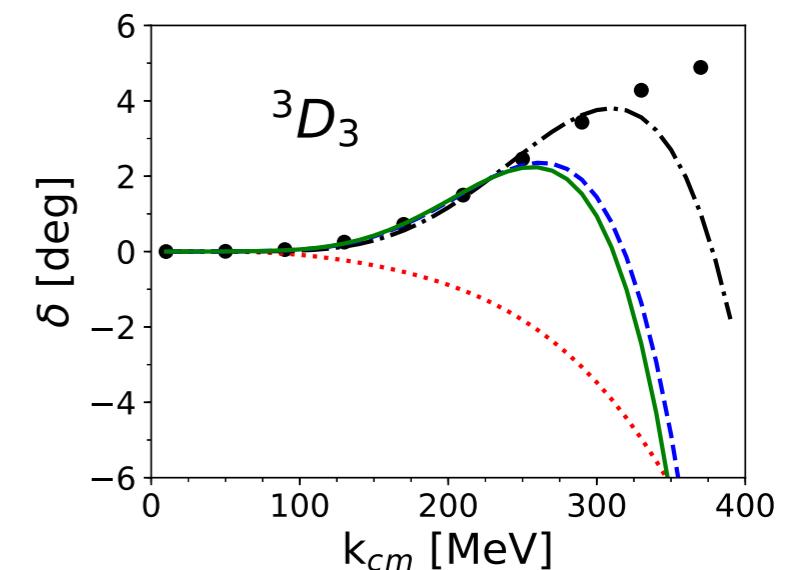


$\mathcal{O}(Q^3)$ variation due to c_i 's

dot-dashed: “NNLO”

dashed: “N₃LO”

solid: “N₄LO”



Summary

- Iso dominated by short-range interactions
- Non-pert. vs. pert. of singular potentials