Recent results in chiral EFT for the two-nucleon system

Dear reader,

These are the slides from my presentation. They do not represent the entire content of the talk. What was actually said is quite important.

Daniel Phillips

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Ohio University

Research supported by the US department of energy

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- Renormalizable order-by-order in this expansion parameter
- Clean living→error estimates, model-independent results
- χPT: low scales: m_π, p; high scales: m_ρ, M_N, $M_\Delta - M_N \equiv \Lambda_{\chi SB}$

Outline

- The proposal: Weinberg's counting for the NN potential, aka naive dimensional analysis for V
- One-pion exchange and renormalization: how strong interactions taught us to be not-quite-as-naïve
- A "new leading order" and its discontents
- Higher orders in χEFT: what comes where?
- Selected applications to EM reactions
- Conclusion

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  Weinberg (1990), apply χPT to V, i.e. expand it in P=($p/\Lambda_{\chi SB}$,$m_\pi/\Lambda_{\chi SB}$)

$$(E - H_0)|\psi\rangle = V|\psi\rangle$$

$$V = V^{(0)} + V^{(2)} + V^{(3)} + \ldots$$

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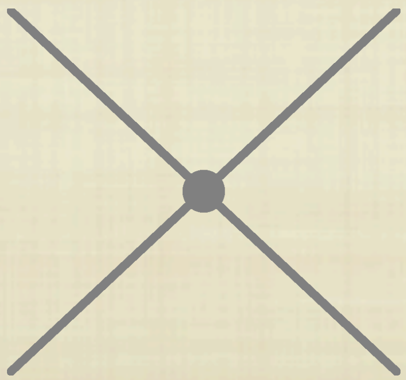
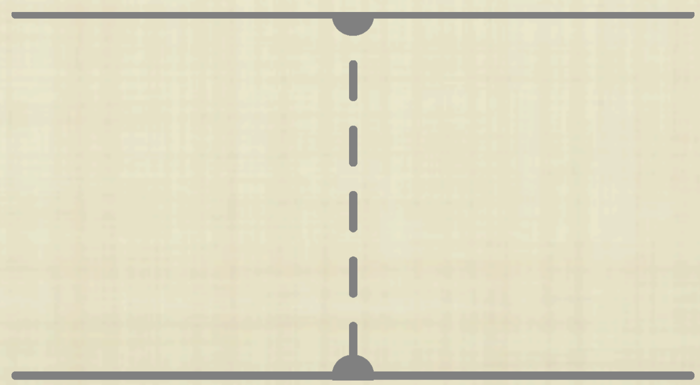
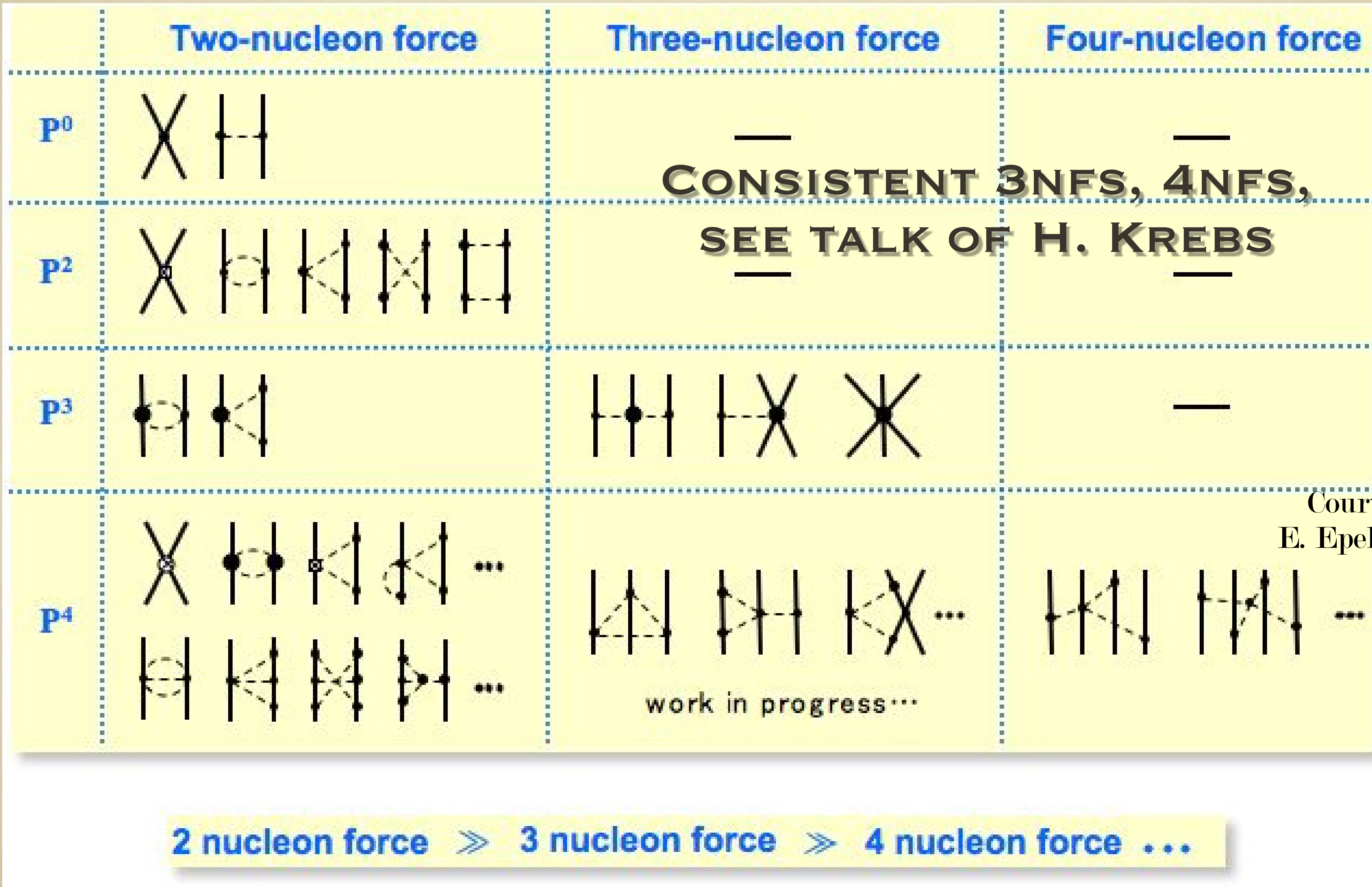
- Leading-order V:

$V^{(0)} =$  $+$  ;

$$\langle \mathbf{p}'|V|\mathbf{p}\rangle = C^{3S1}P_{3S1} + C^{1S0}P_{1S0} + V_{1\pi}(\mathbf{p}' - \mathbf{p})$$

Higher orders in V

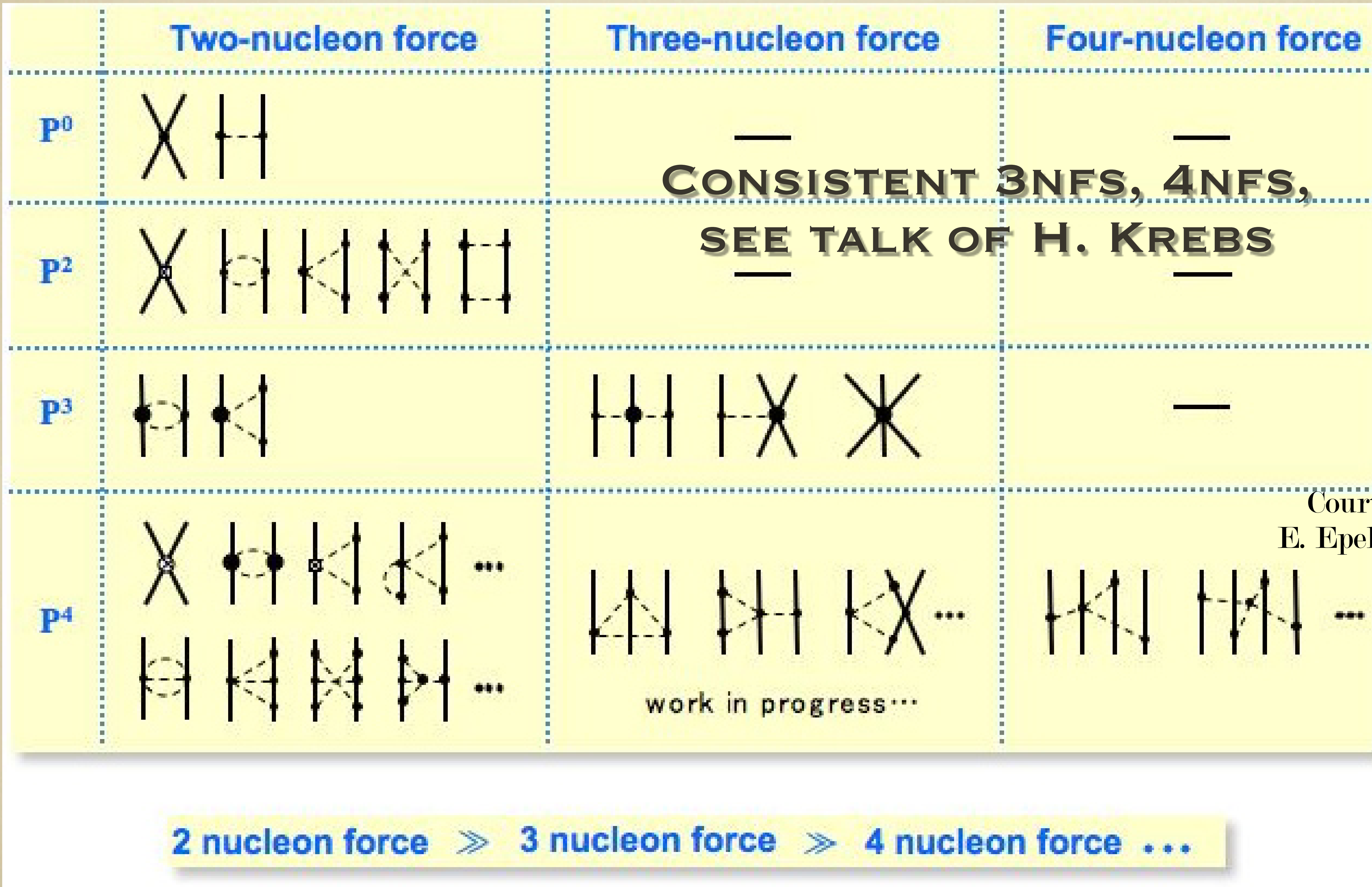


CONSISTENT 3NFS, 4NFS, SEE TALK OF H. KREBS

Courtesy
E. Epelbaum

Higher orders in V

(Ordonez, Ray, van Kolck; Kaiser, Brockmann, Weise; Epelbaum, Meissner, Gloeckle; Entem, Machleidt)



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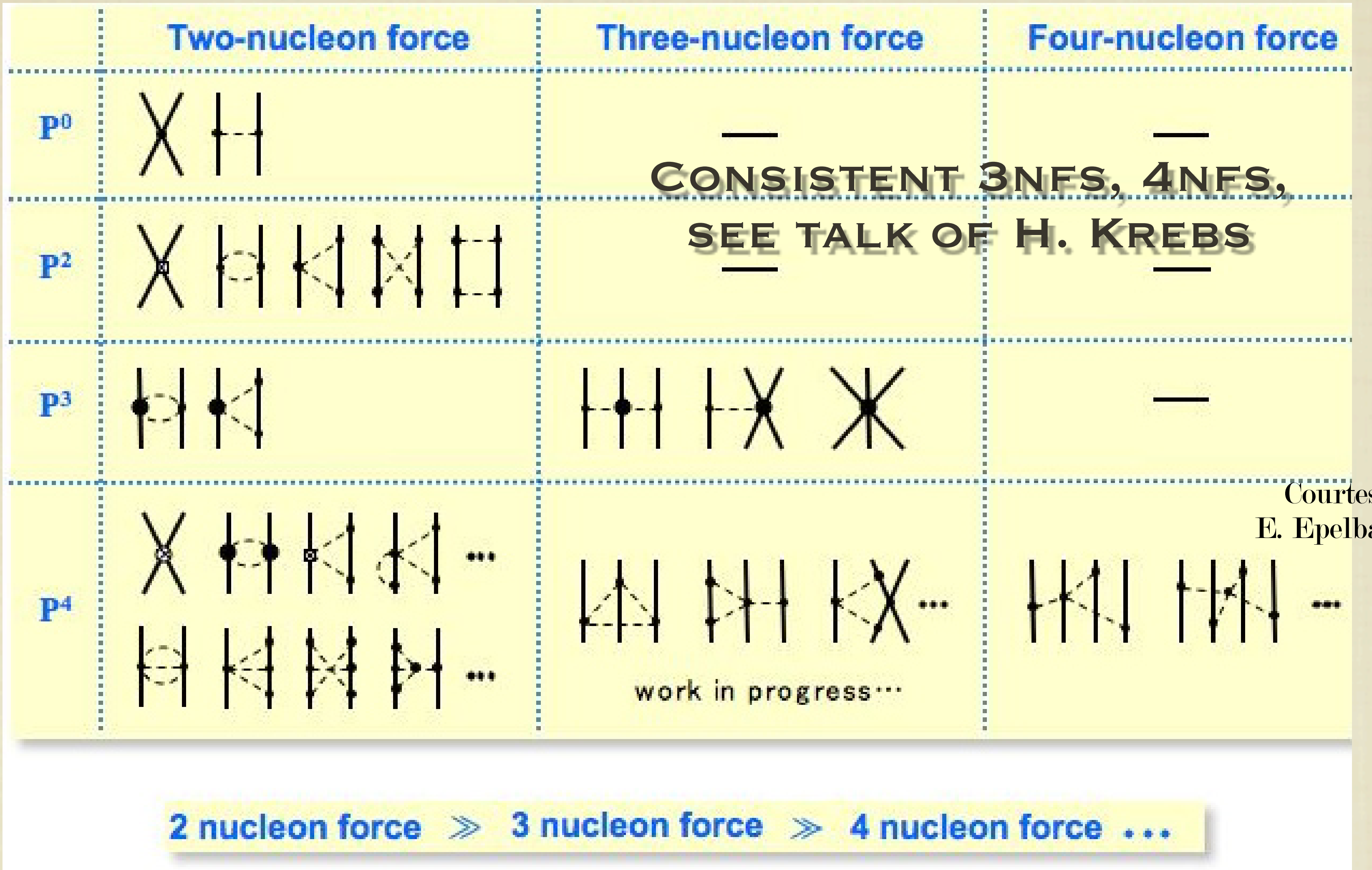

Consistent 3NFs, 4NFs, see talk of H. Krebs

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- No difficulties with counting for long-distance pieces

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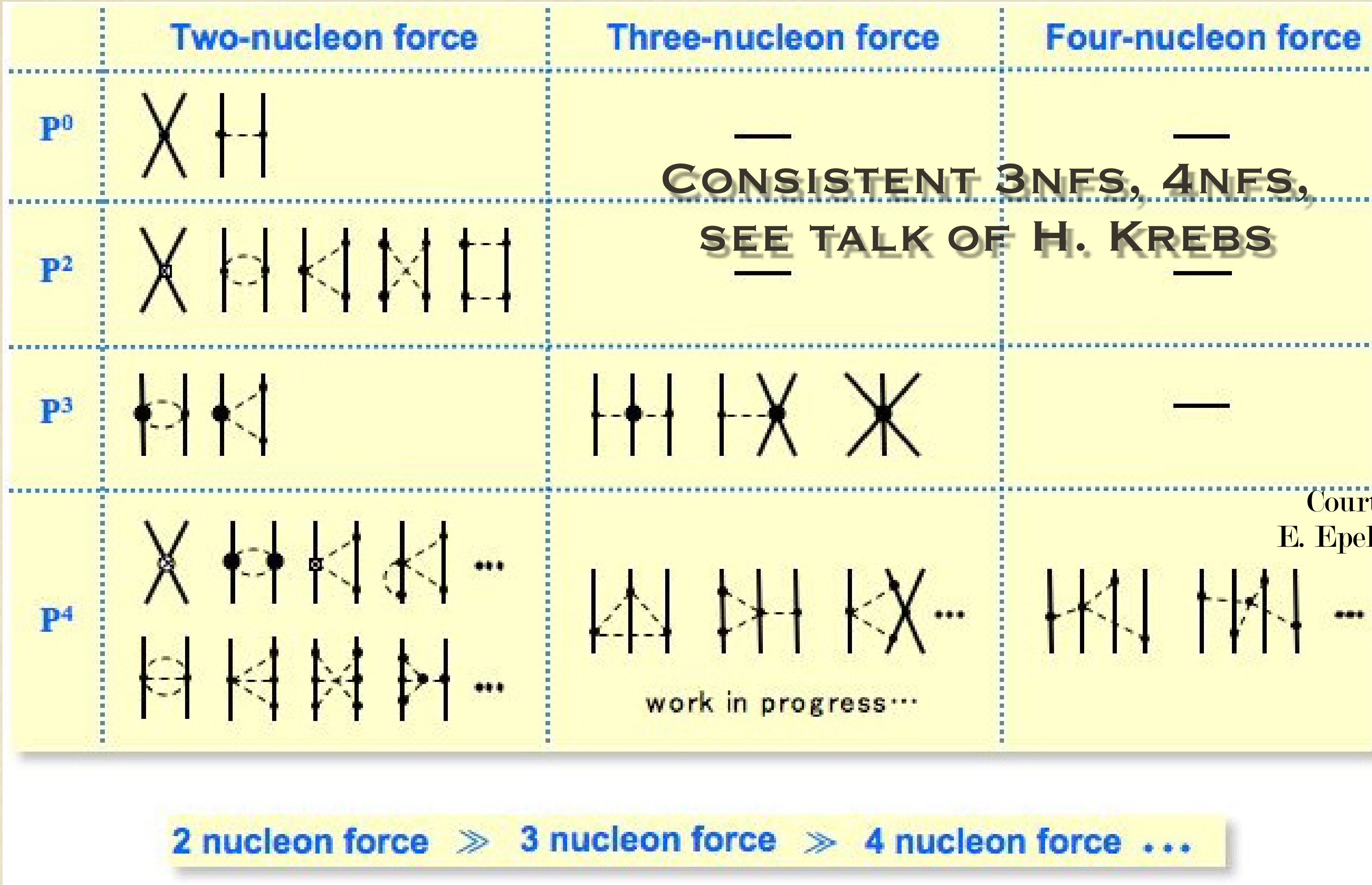

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- Here I present discussion of “Delta-less” potential

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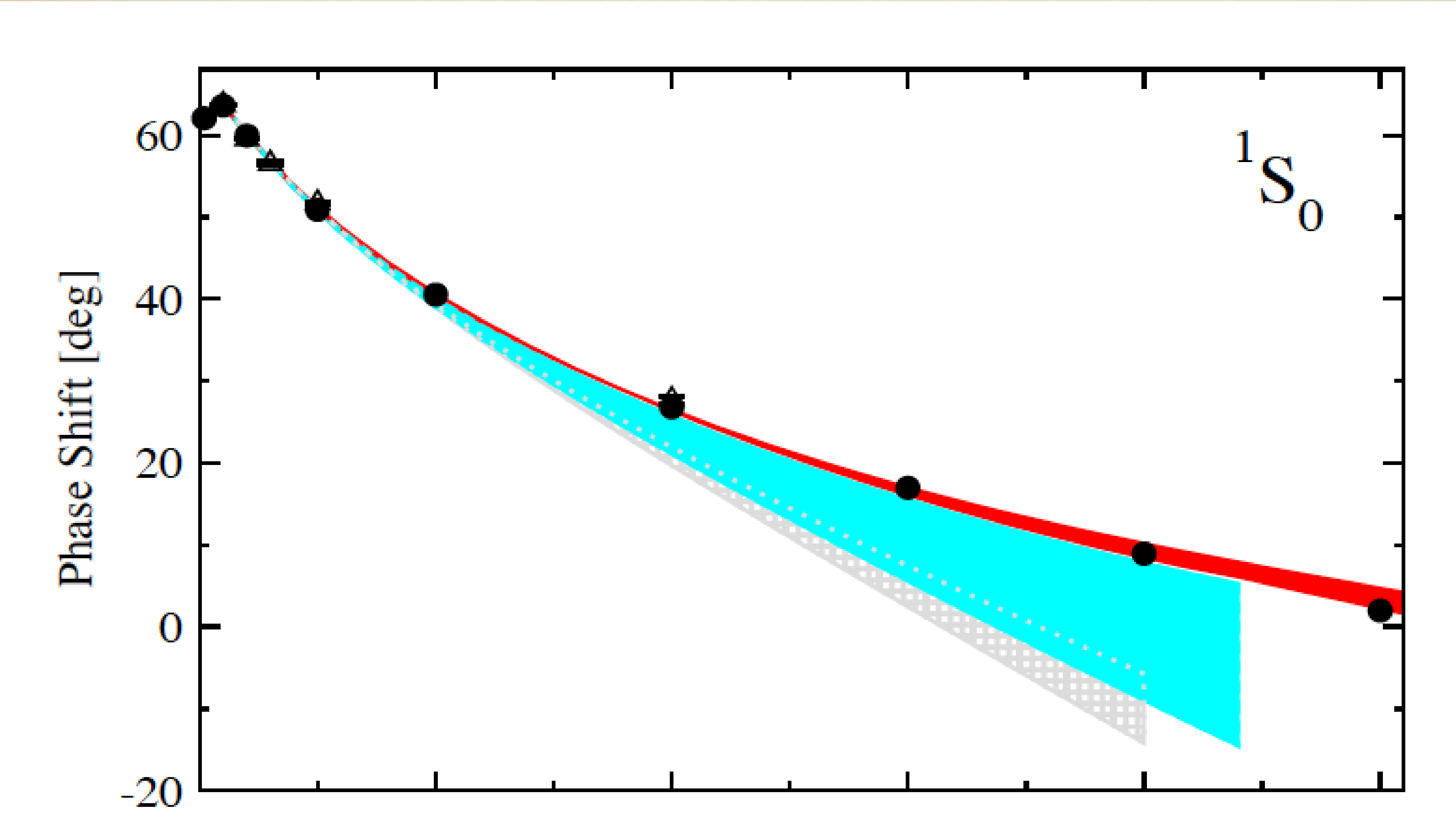
Epelbaum, Meissner, Gloeckle (2005)



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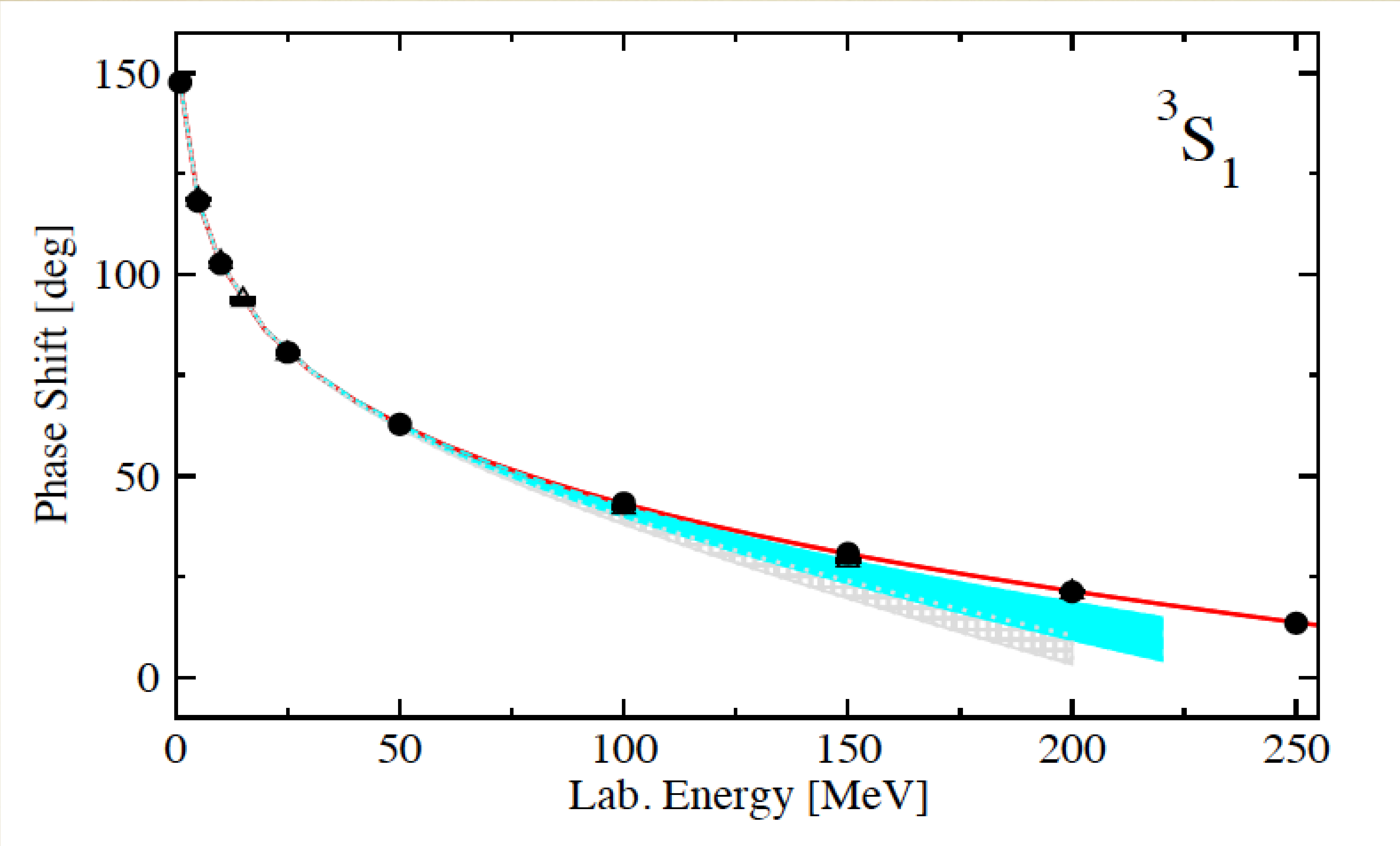

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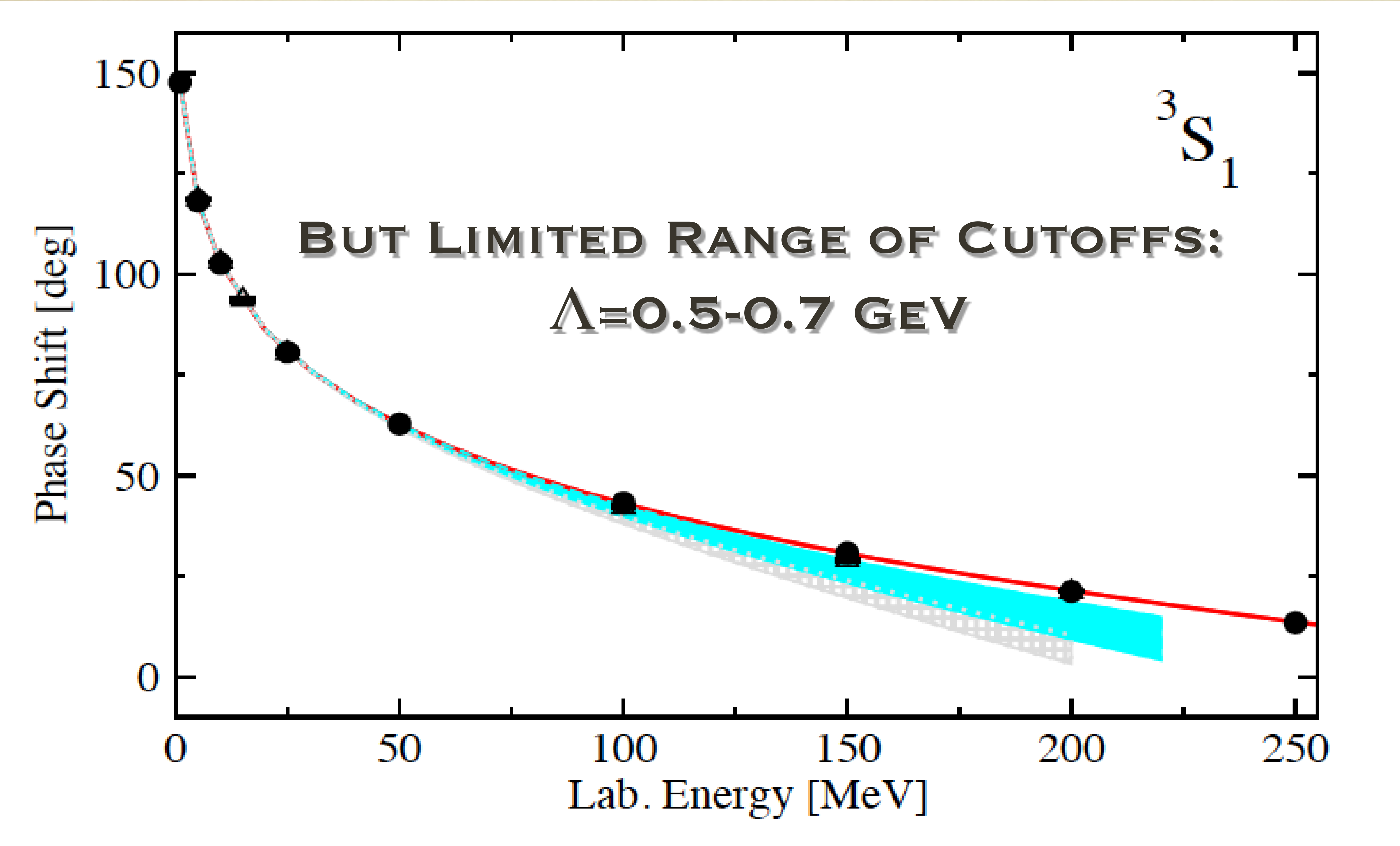

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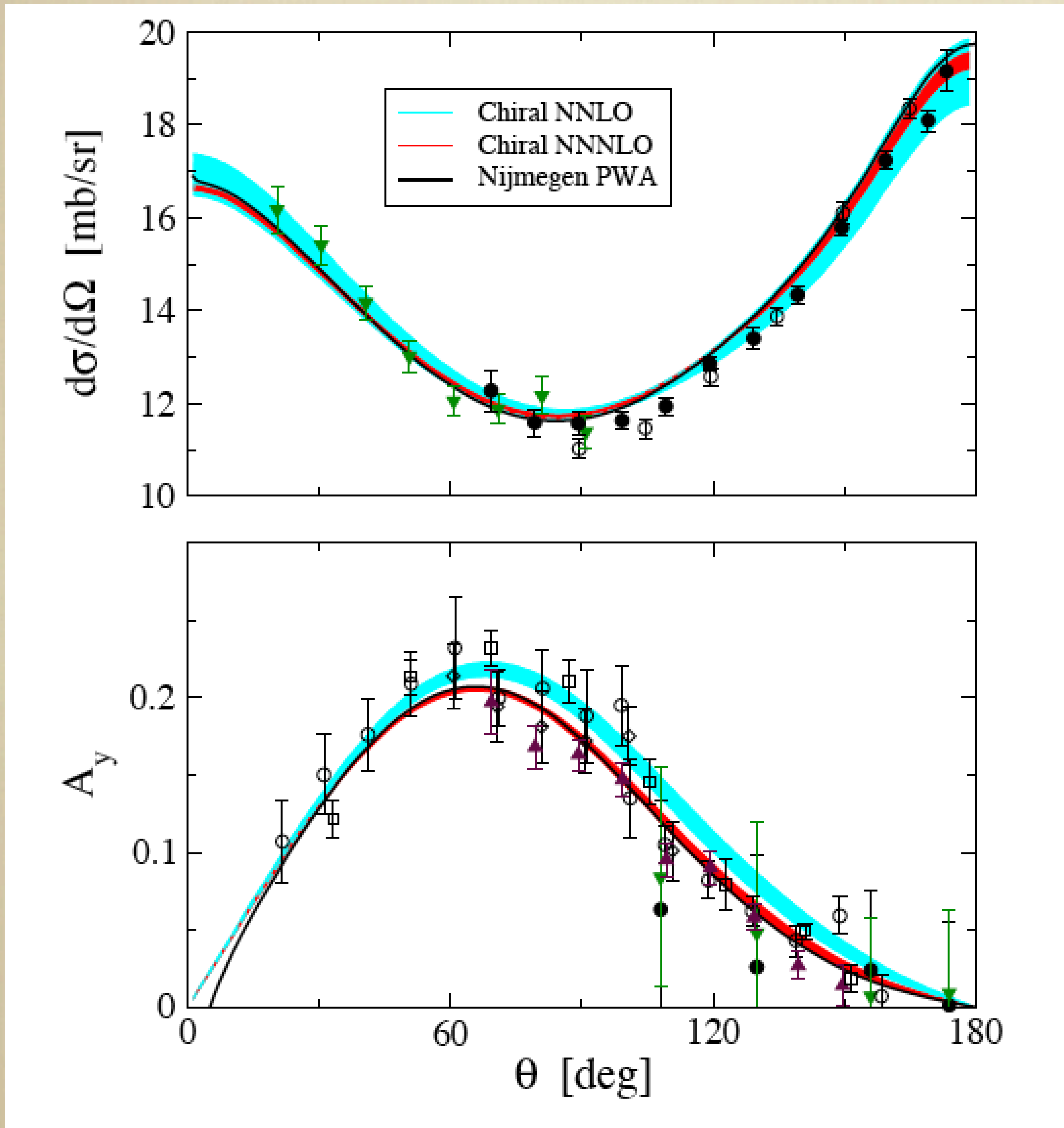

T_{lab}=50 MeV

- N^3LO potential, χ^2/dof comparable to AV18.

Entem, Machleidt (2003)

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- Reproduce A=3 and 4 observables

  Epelbaum, Nogga, et al.(2002)

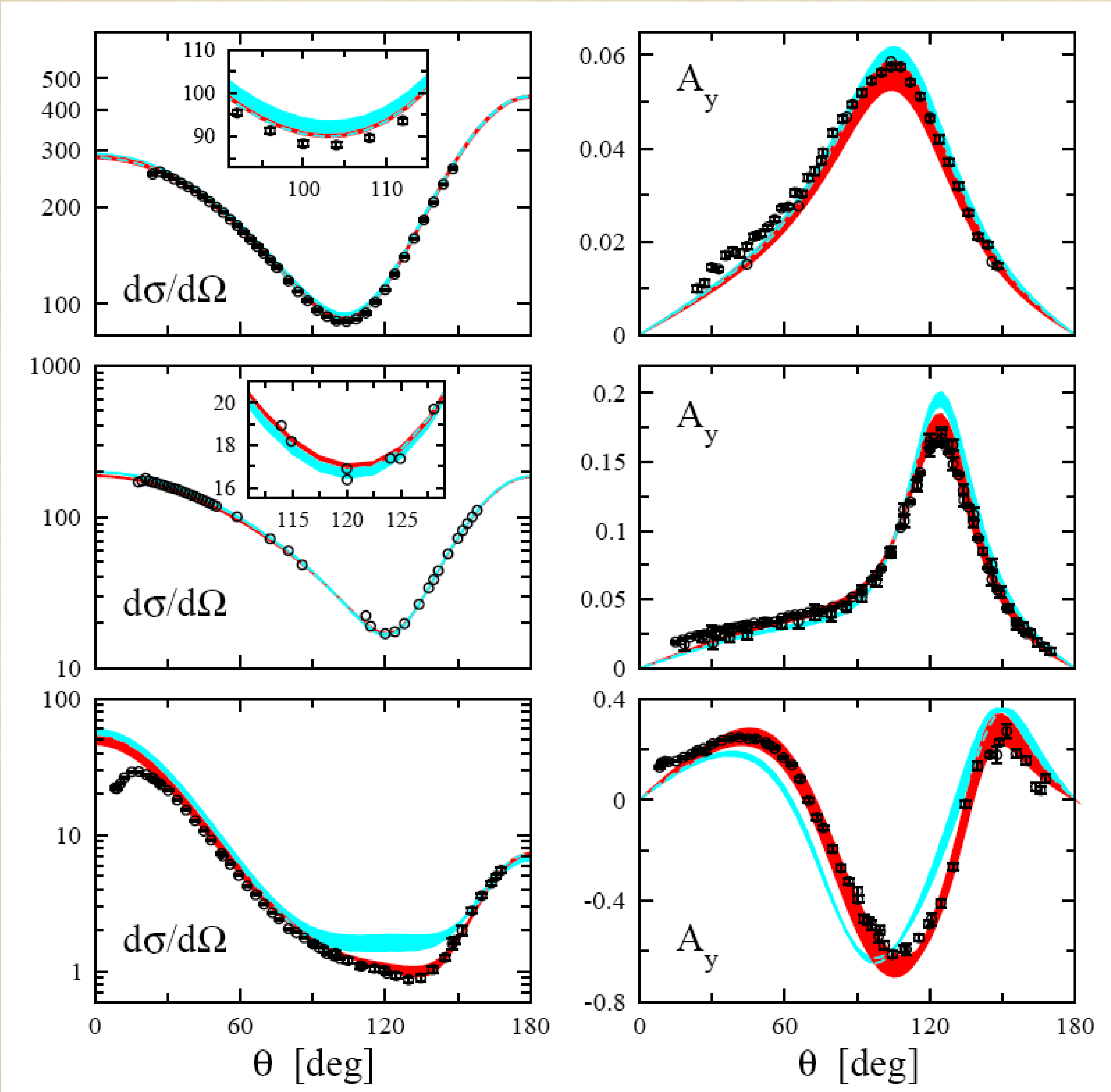
	NLO	NNLO	"Exp."
^{3}H	-7.53..-8.54	-8.68	-8.68
^{4}He	-23.87..-29.57	-29.51..-29.98	-29.6

Successes in A=2-4

E=3 MeV

E=10 MeV

E=65 MeV



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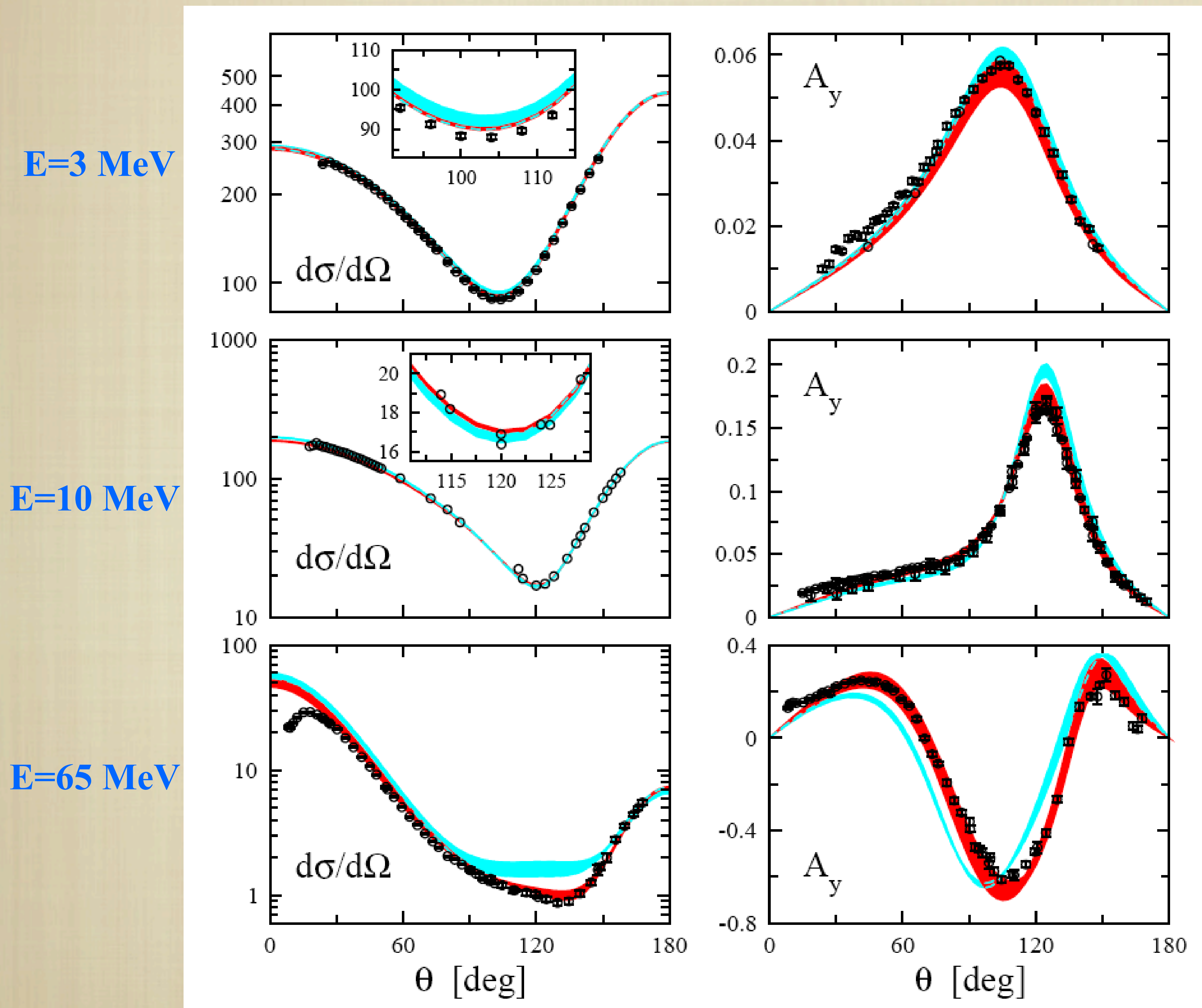

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- Applications to many-body systems: see talk of R. Roth

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Goal: once we understand what terms are present in χEFT up to some order, we can include them in a potential, and use it with a low cutoff in order to do nuclear physics calculations

Fun facts about one-pion exchange

$$V(\mathbf{r}) = \tau_1^a \tau_2^a \left[\sigma_1 \cdot \sigma_2 Y(r) + S_{12}(\hat{r}) T(r)\right]$$

$$S_{12}(\hat{r}) = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \cdot \sigma_2;$$

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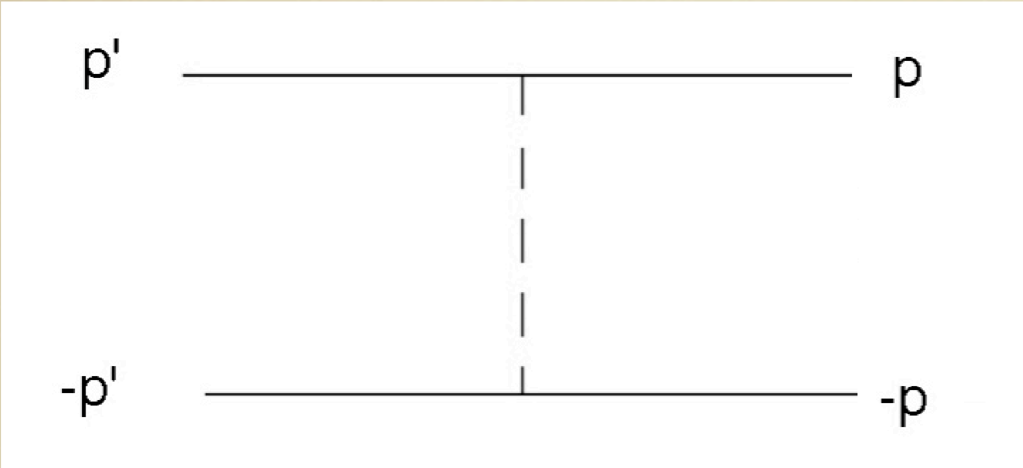

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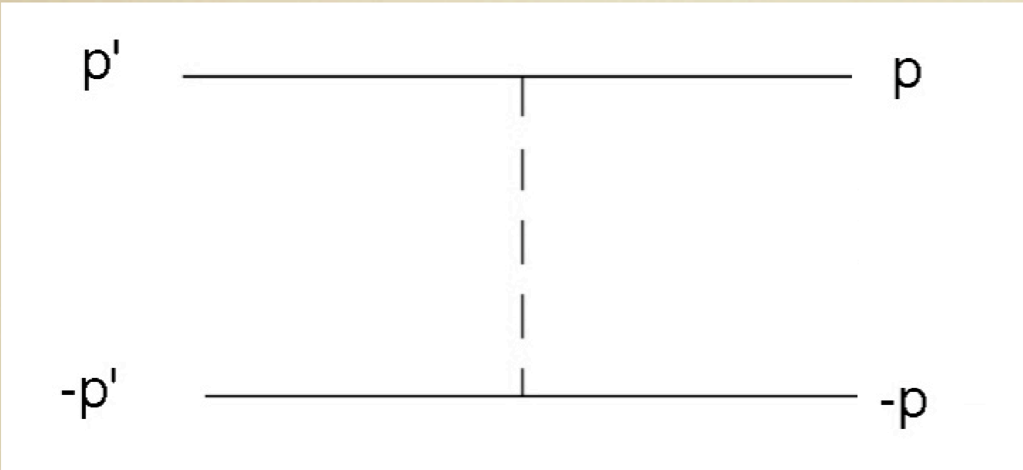

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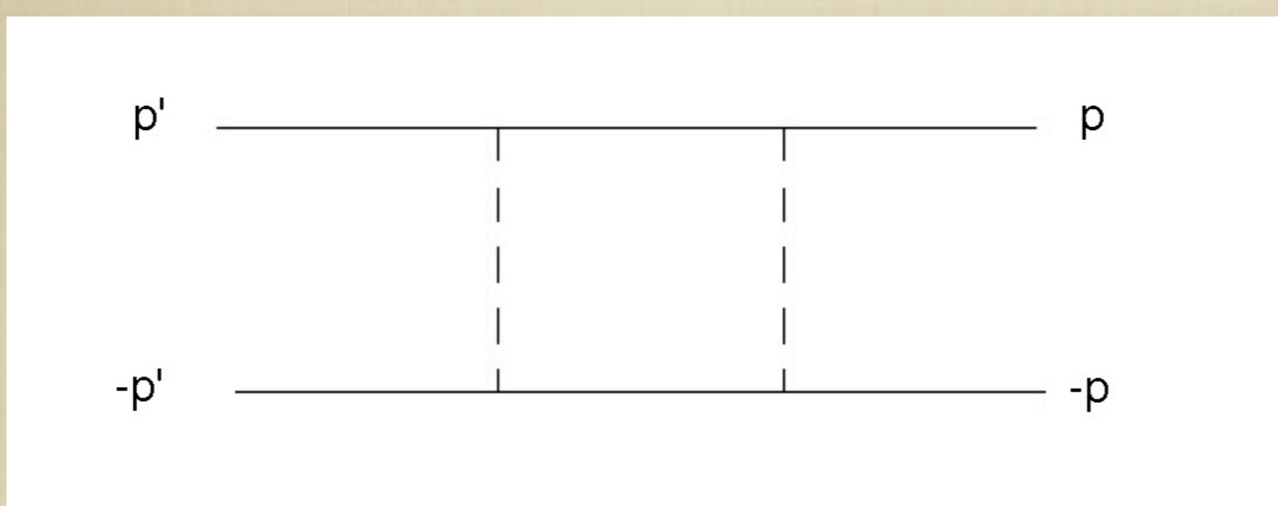
- Momentum scales present: m_π and $\Lambda_{NN} = \dfrac{16\pi f_\pi^2}{g_A^2 M} \approx 300$ MeV
- χSB predicts $1/r^3$ potential that couples waves with ΔL=2
- Tensor part of 1π exchange does not appear for S=0
- $1/r^3$ part of 1π exchange “screened” by centrifugal barrier for large L

The quest for leading order I



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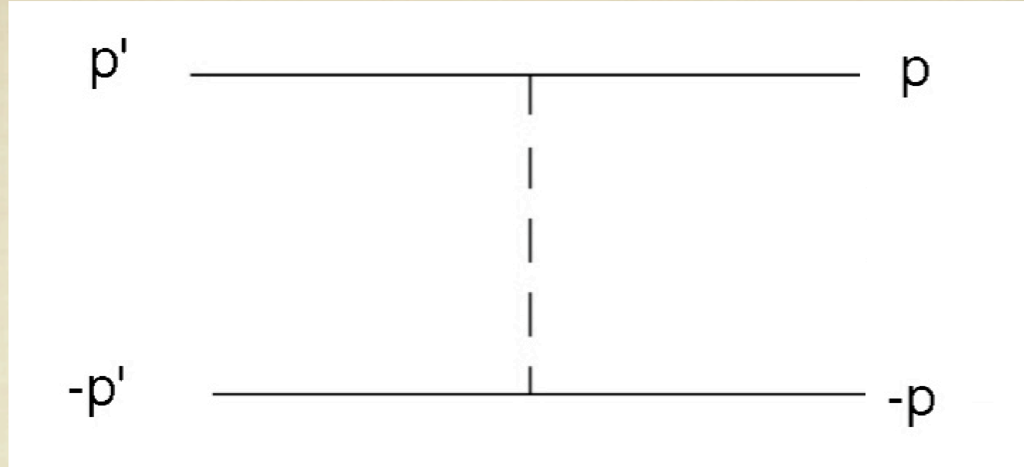

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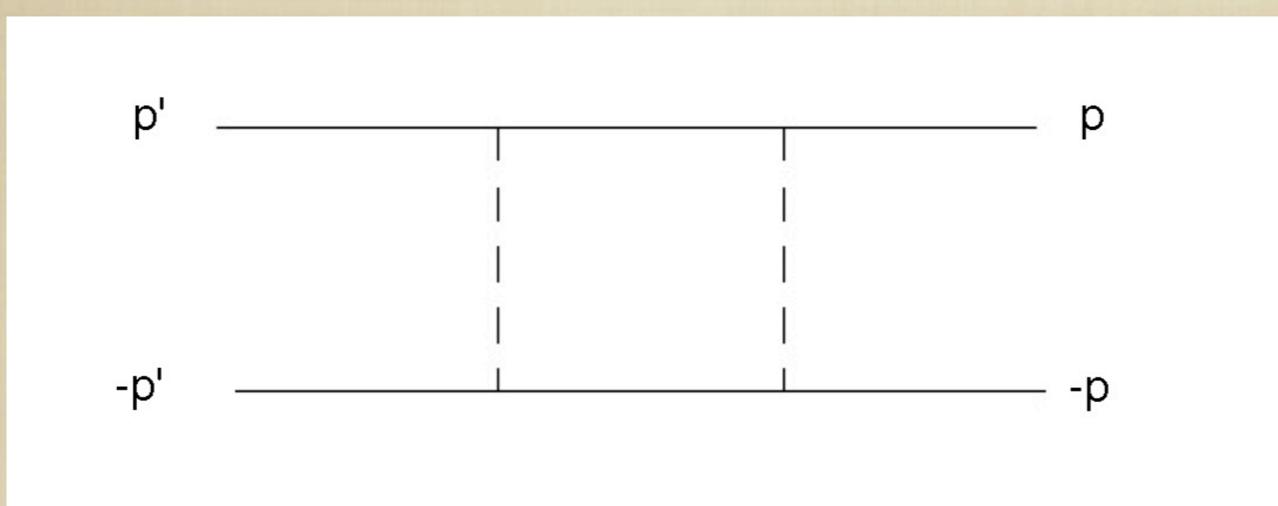

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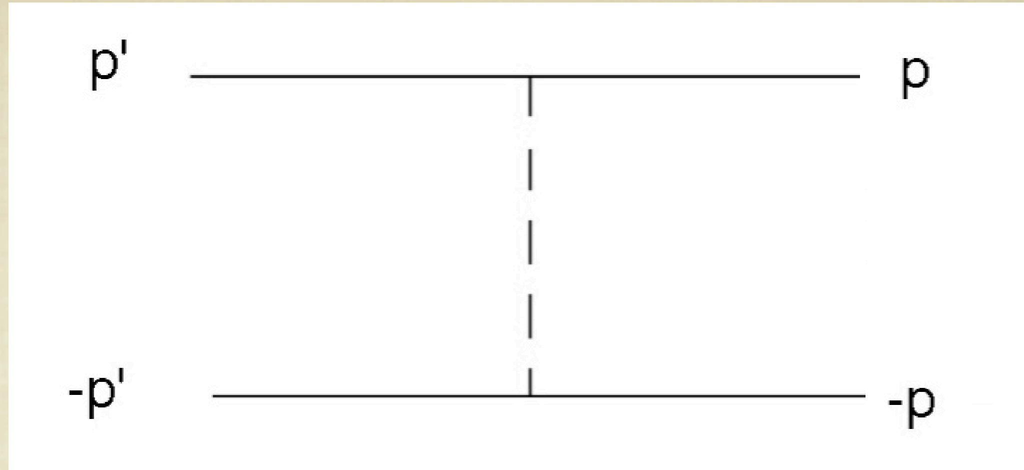

- Iterates of one-pion exchange become comparable with tree-level for momenta of order Λ_{NN}...in low partial waves

Fleming, Mehen, Stewart (2000); Beane, Bedaque, Savage, van Kolck (2002); Birse (2006)

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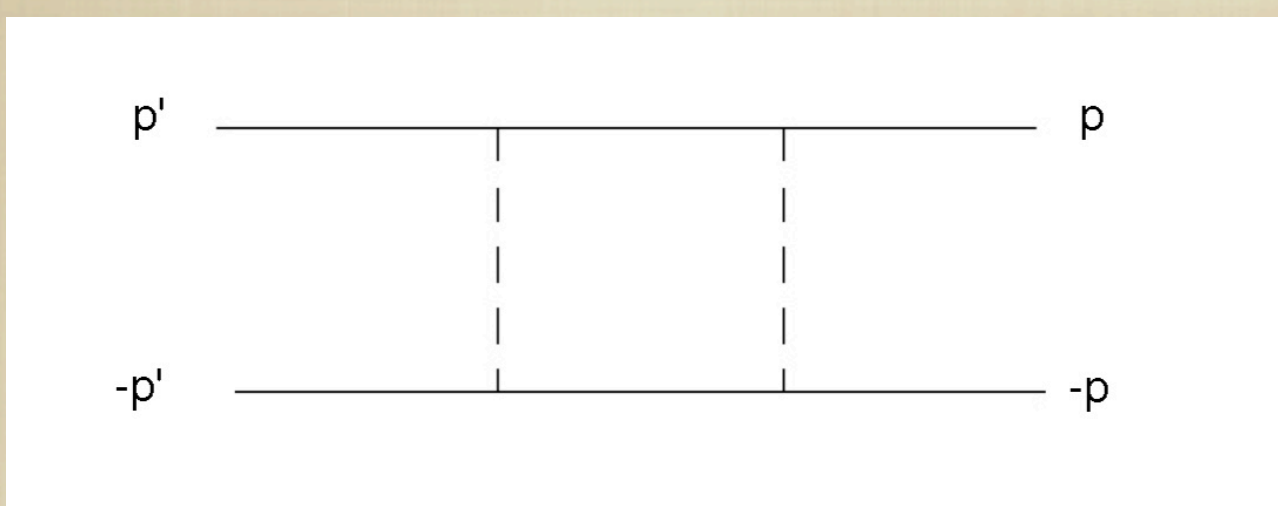

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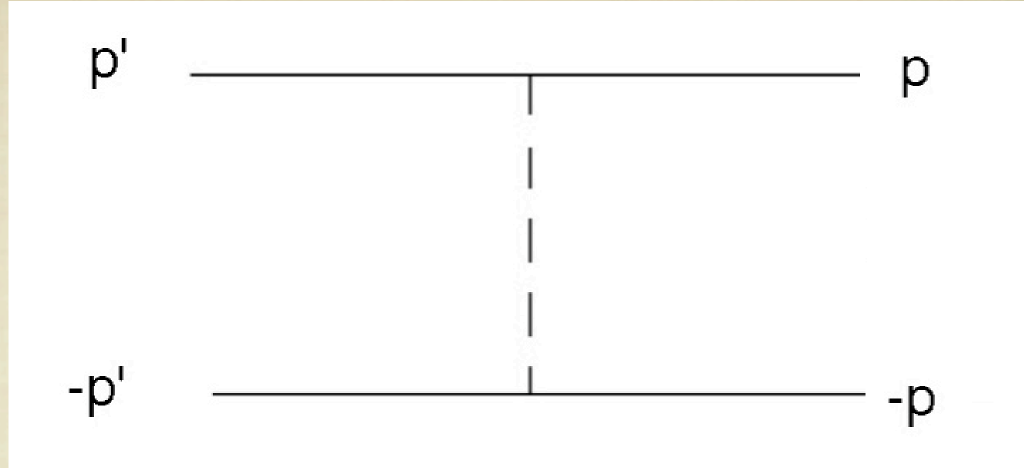

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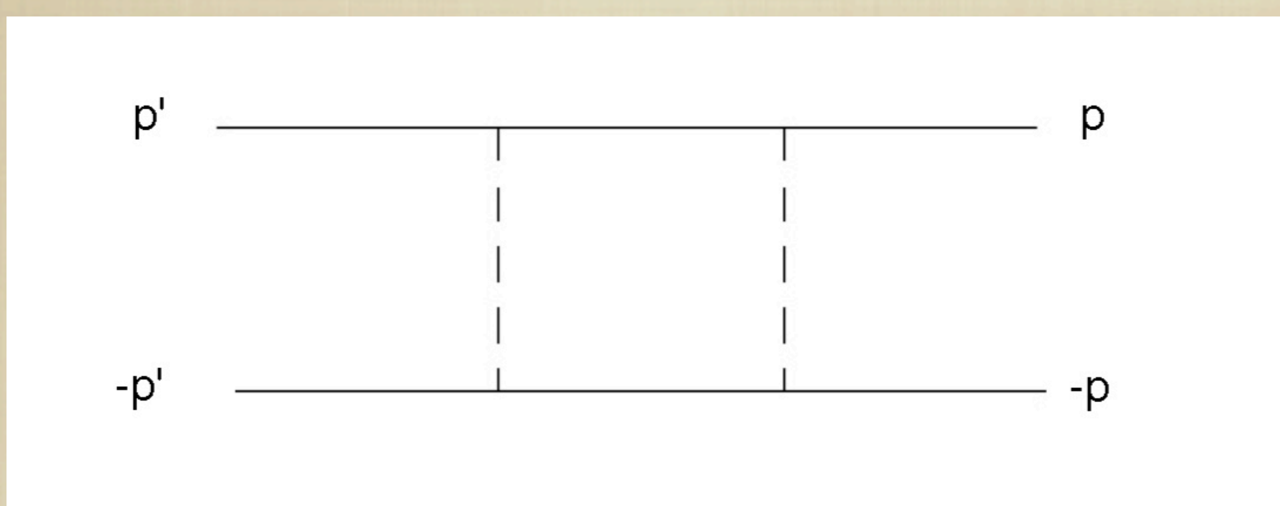

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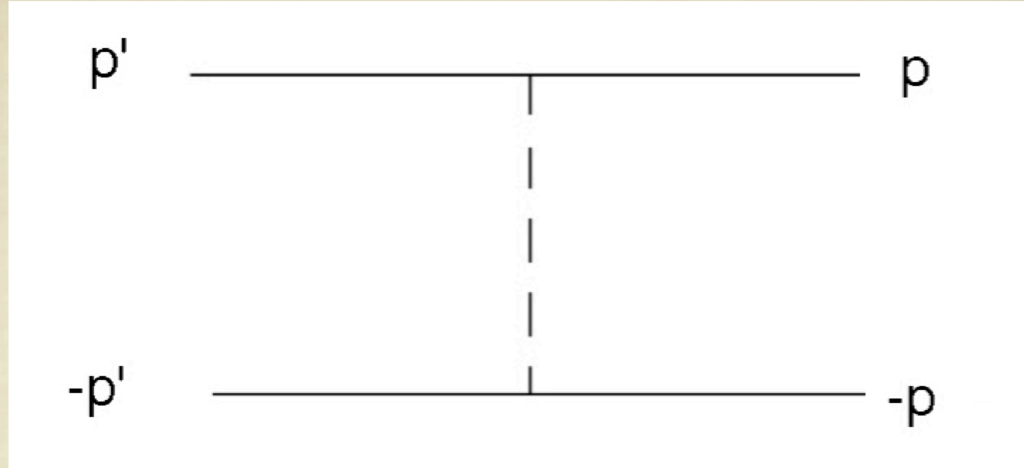

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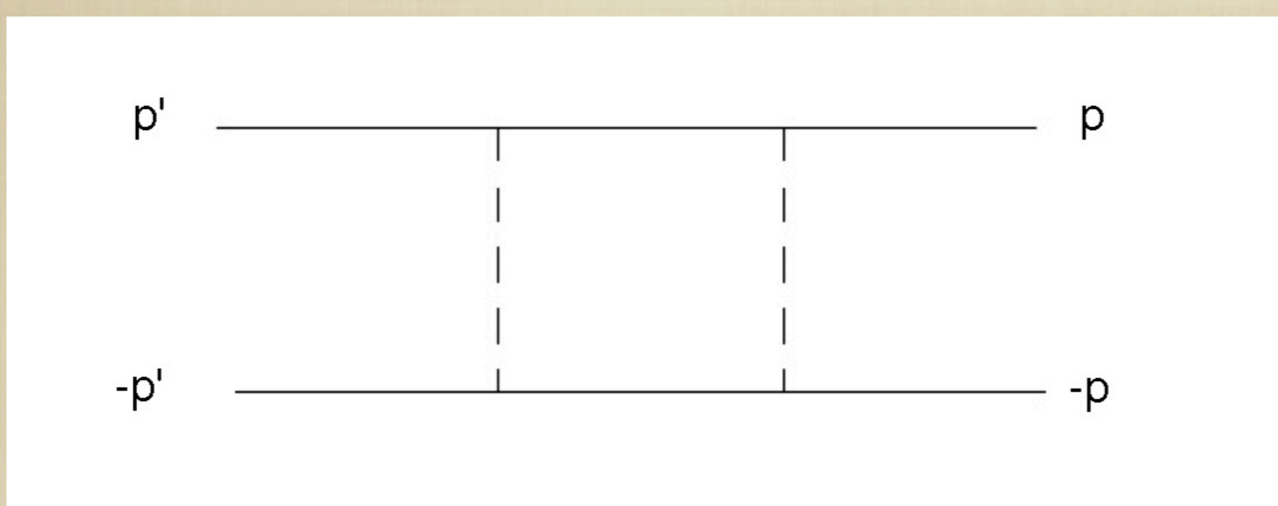

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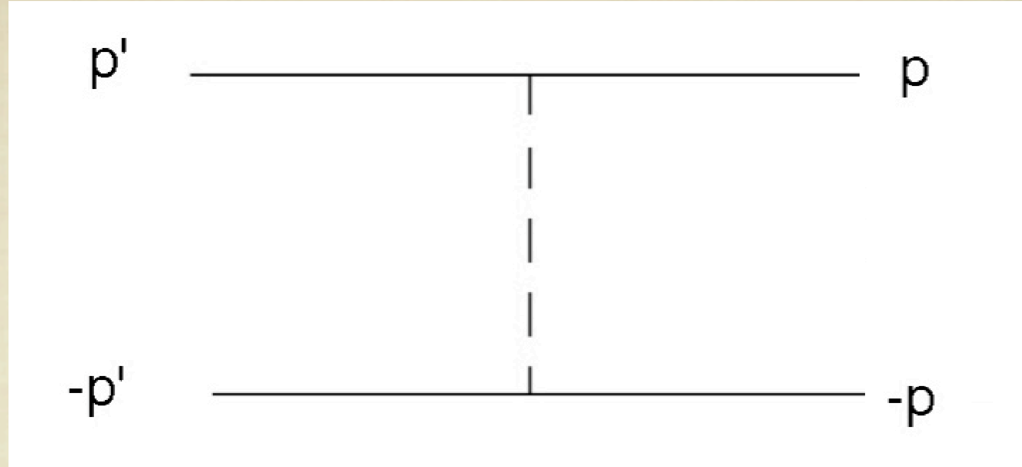

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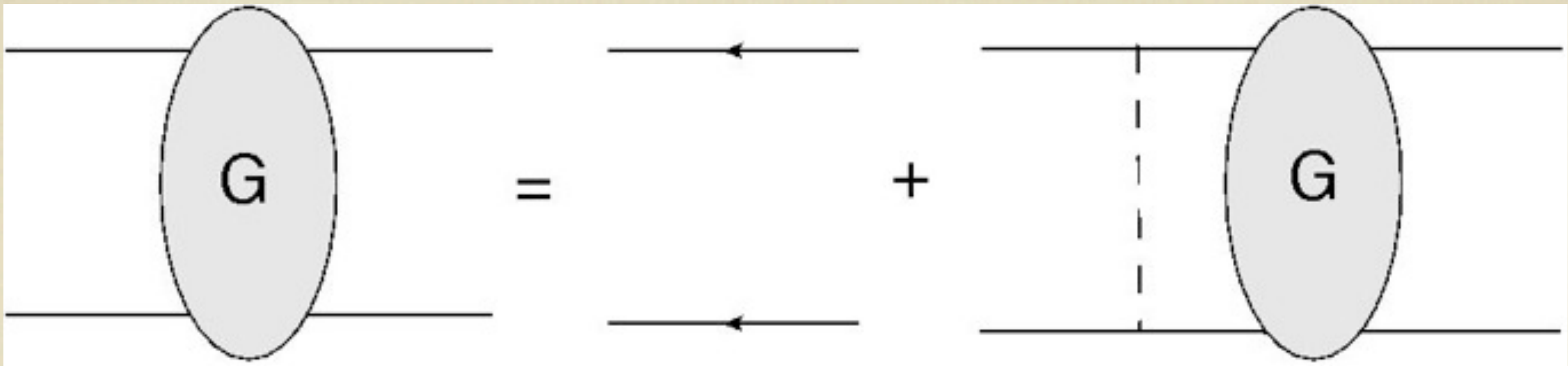
- Perturbation theory should also be OK for: (a) higher partial waves, (b) 1π exchange in singlet waves, (c) $p \ll \Lambda_{NN}$

The quest II: to iterate or not to iterate



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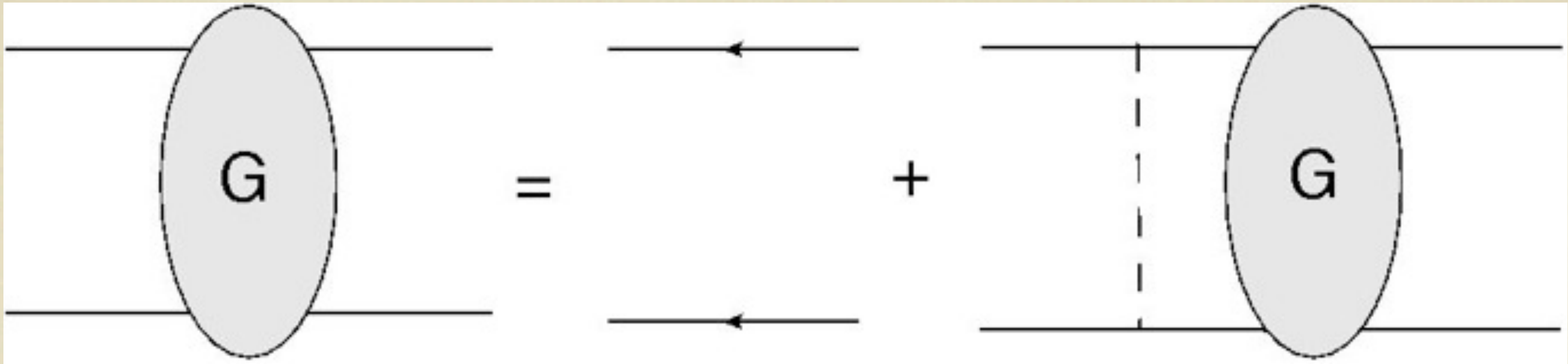
- "Sum up" $V_{OPE} + V_{OPE} G_0 V_{OPE} + ...$



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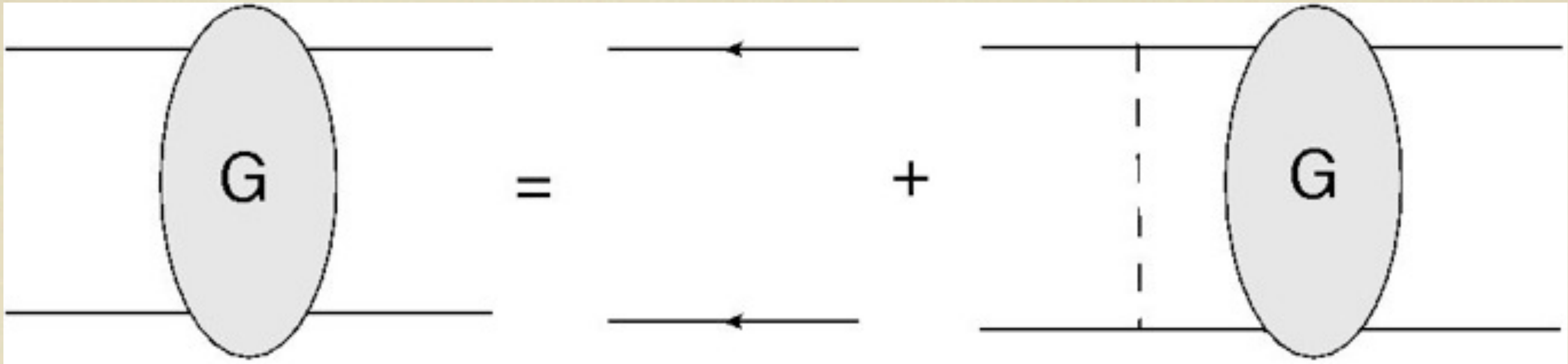

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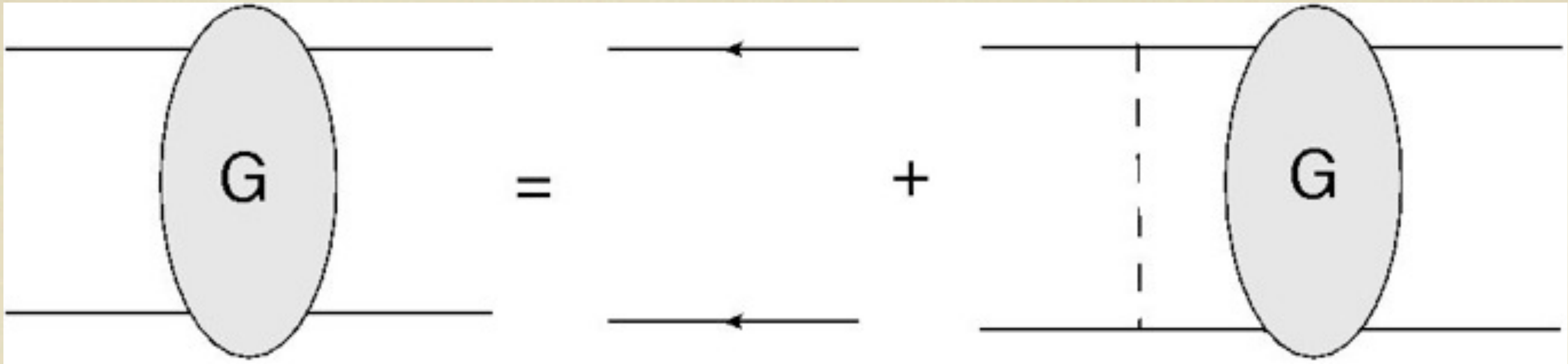

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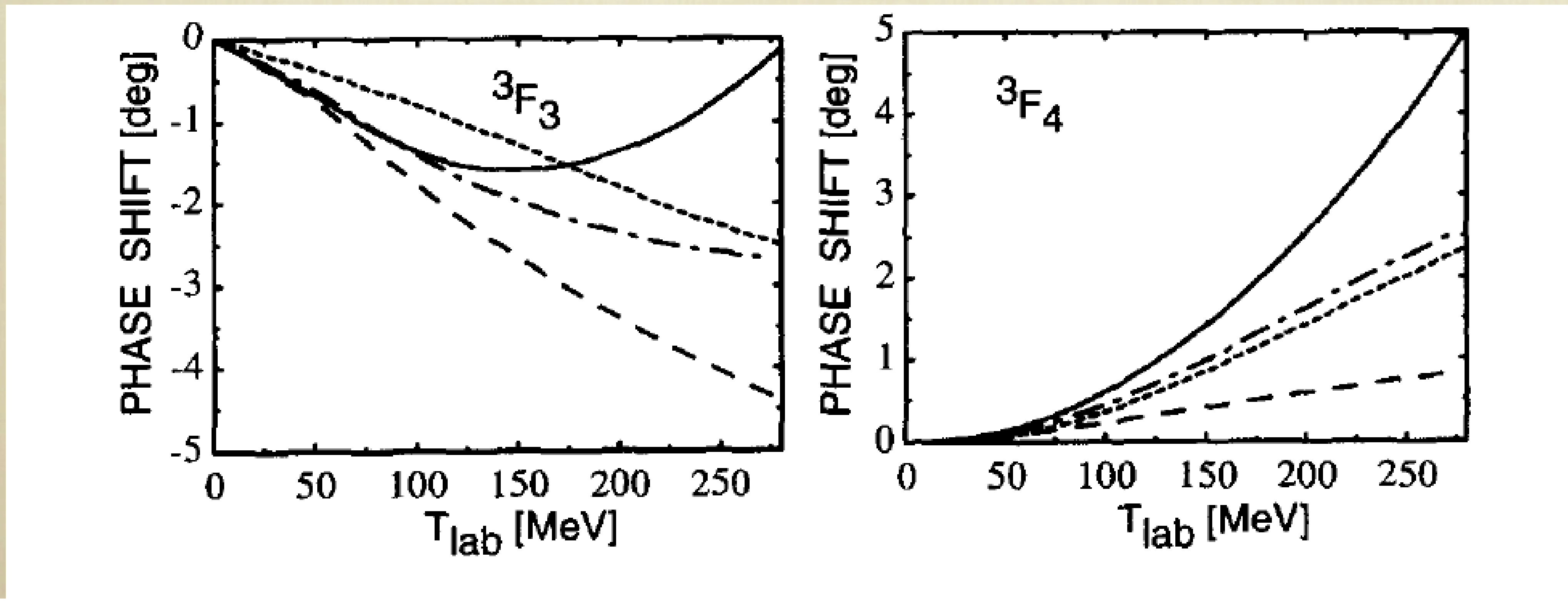
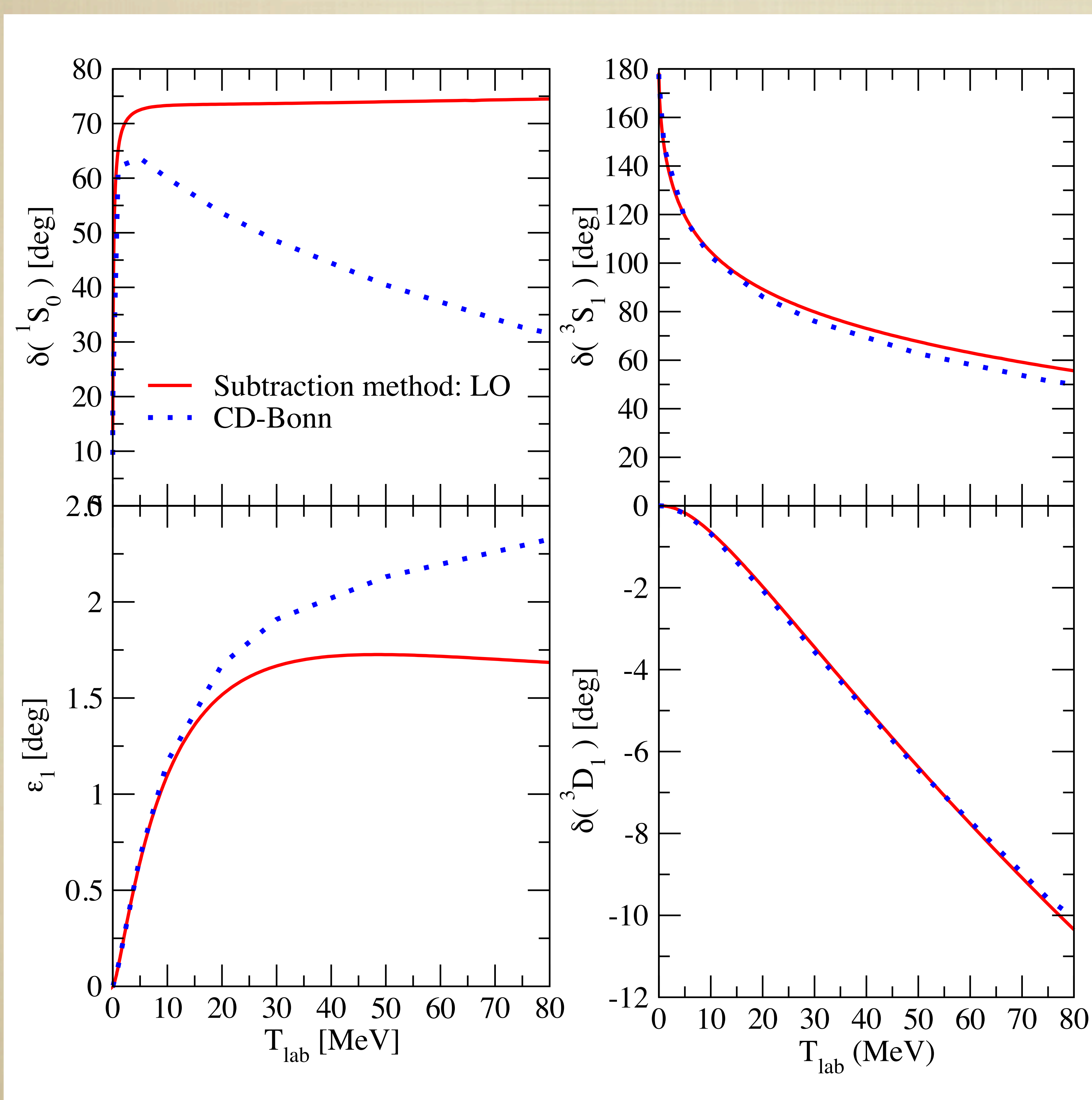
Kaiser, Brockmann, Weise (1997)



Standard χPT

The quest III: S waves

Beane, Bedaque, Savage, van Kolck (2002);
Pavon Valderrama, Ruiz Arriola (2005)



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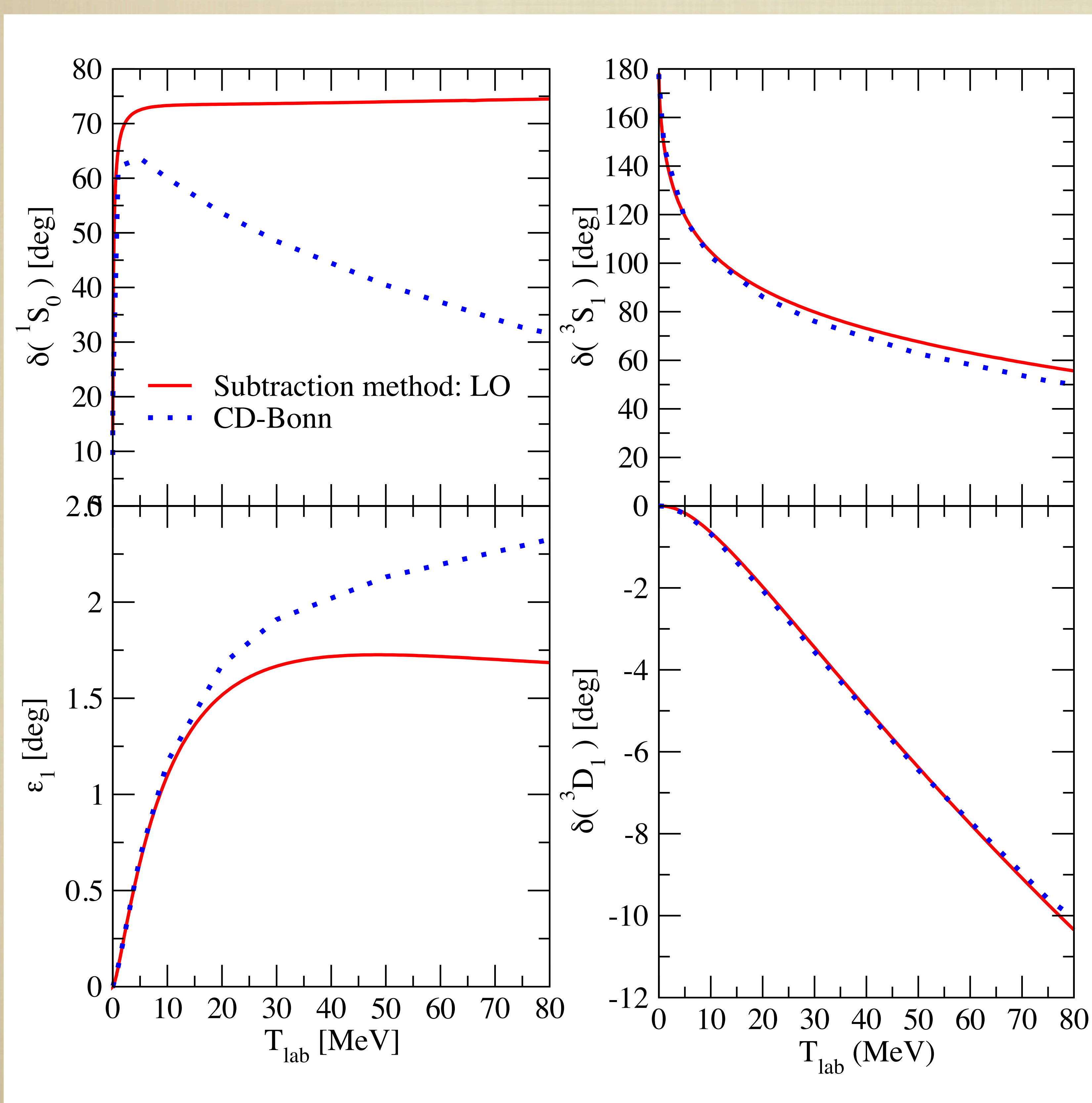

- Stable for wide range of cutoffs
- Subtractive renormalization numerically efficient

Yang, Elster, Phillips (2007)

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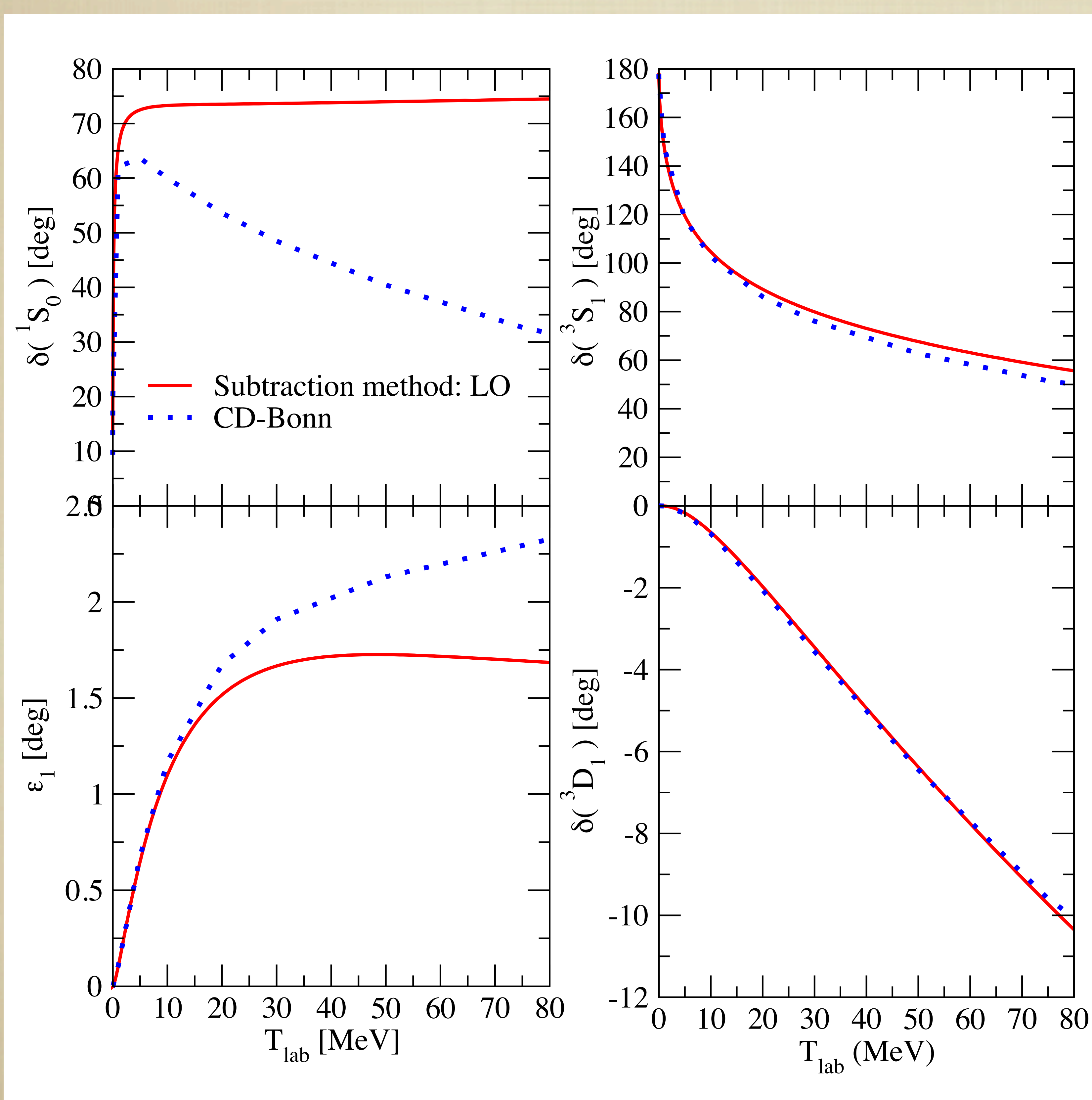

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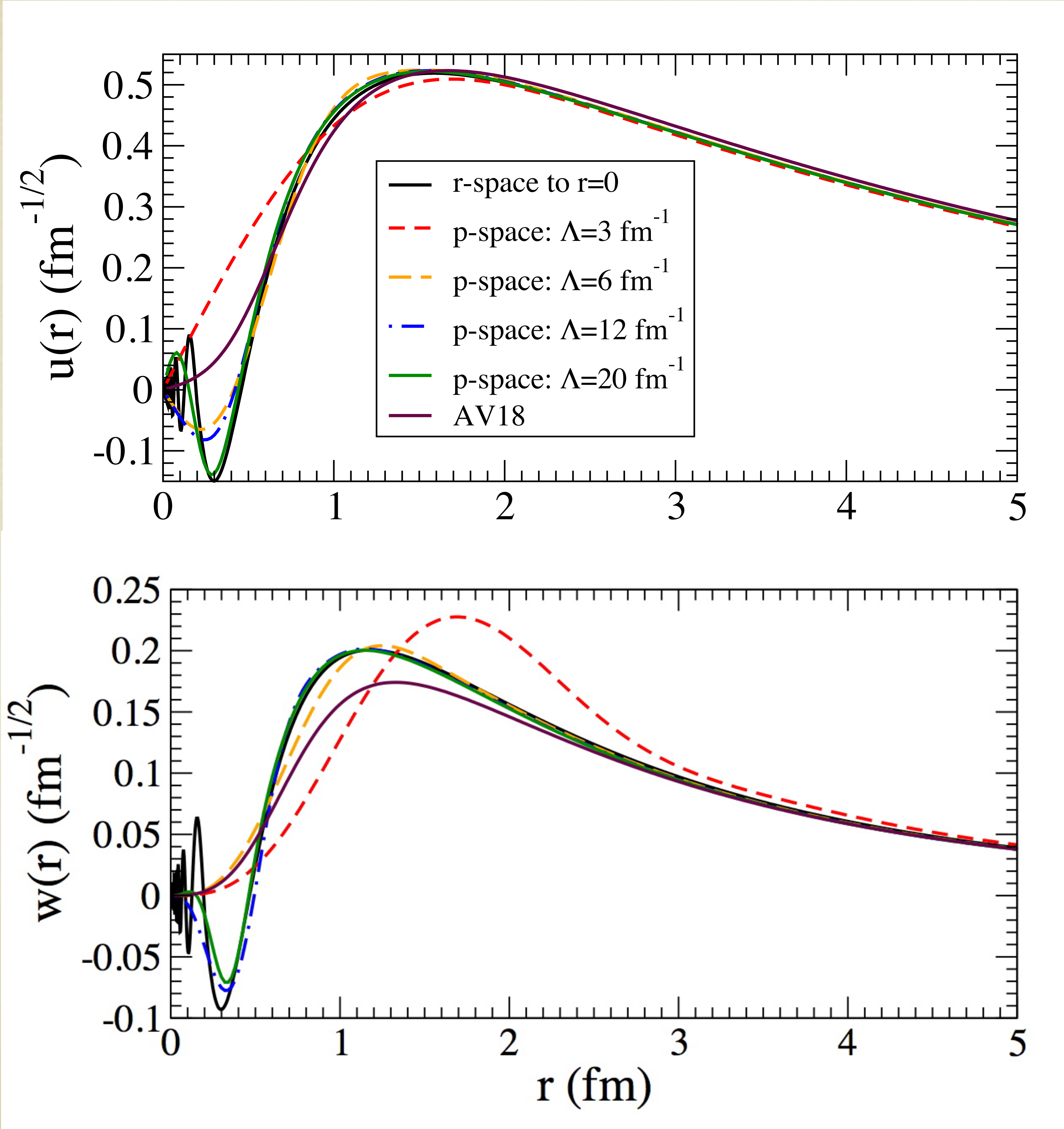
- One-pion exchange weak in $^1S_0$

χEFT deuteron wave functions at leading order

Pavon Valderrama, Nogga, Ruiz Arriola,DP, EPJA 36, 315 (2008)



The quest IV: solving the $1/r^3$ potential

Case (1950), Sprung et al. (1994),
Beane et al. (2001),
Pavon Valderrama, Ruiz Arriola (2004-6)

- Attractive case, for $r \ll 1/\Lambda_{NN}$

$$u_1(r) = (\Lambda_{NN} r)^{3/4} \cos\left(4\sqrt{\frac{1}{\Lambda_{NN} r}}\right); u_2(r) = (\Lambda_{NN} r)^{3/4} \sin\left(4\sqrt{\frac{1}{\Lambda_{NN} r}}\right)$$

- Equally regular solutions, need boundary condition to fix phase

- c.f. $j_l(kr)$ and $n_l(kr)$ for plane waves as $r \to 0$

- Repulsive, for $r \ll 1/\Lambda_{NN}$

$$u_1(r) = (\Lambda_{NN} r)^{3/4} \exp\left(4\sqrt{\frac{1}{\Lambda_{NN} r}}\right); u_2(r) = (\Lambda_{NN} r)^{3/4} \exp\left(-4\sqrt{\frac{1}{\Lambda_{NN} r}}\right)$$

- Still need boundary condition to fix "phase", but results insensitive to choice

The quest V: power counting

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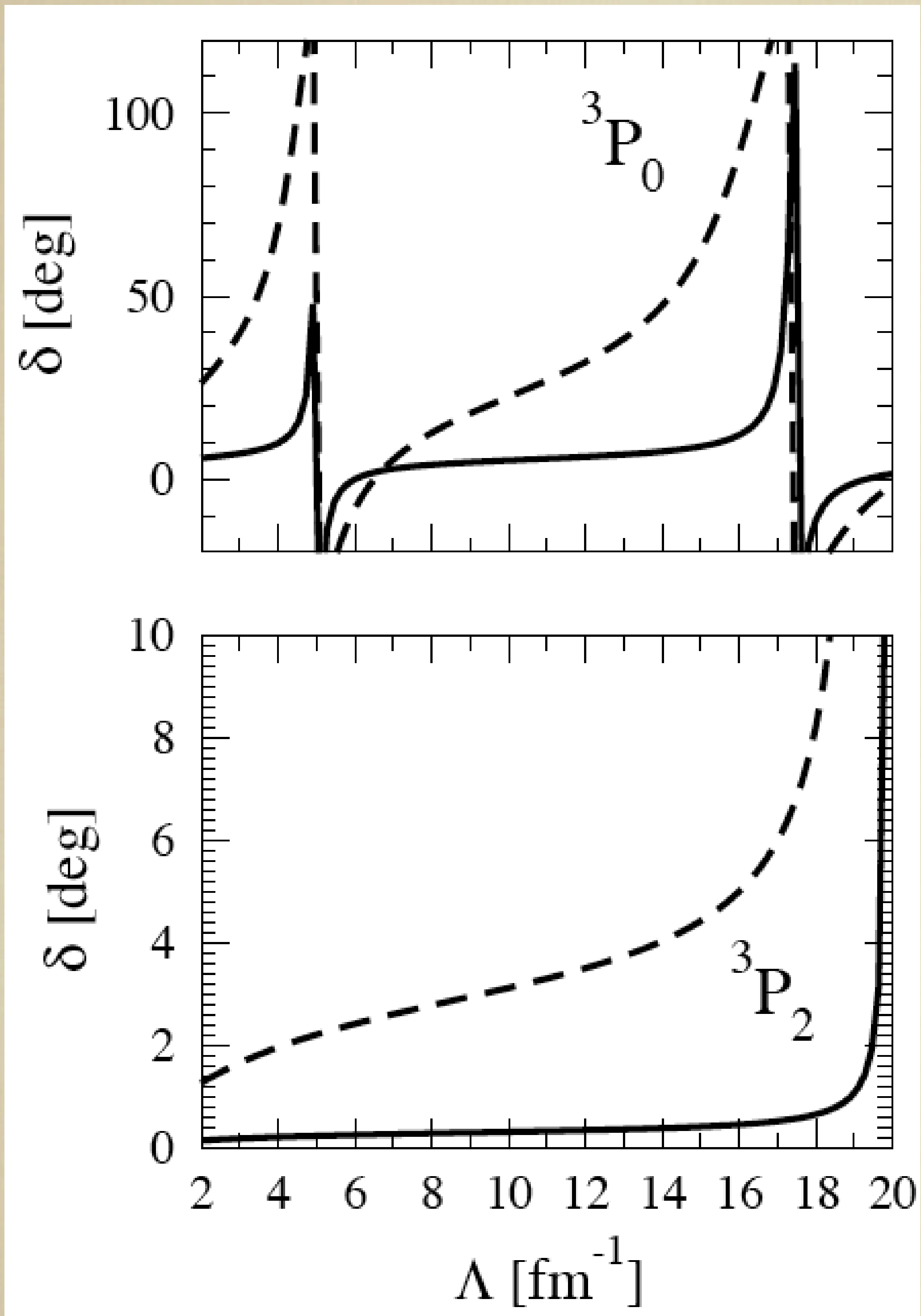

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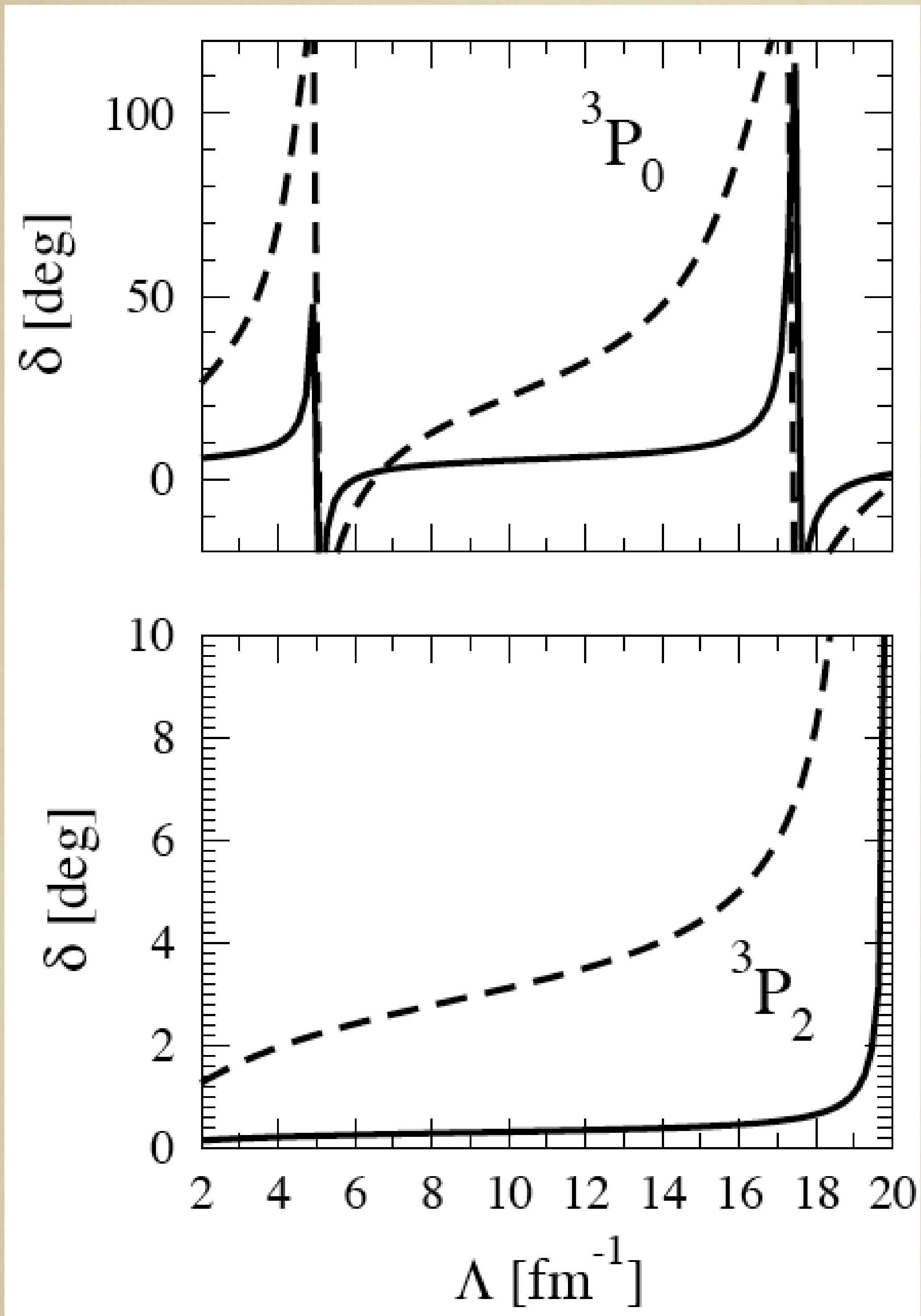

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Eiras, Soto (2002); Nogga, Timmermans, van Kolck (2005)

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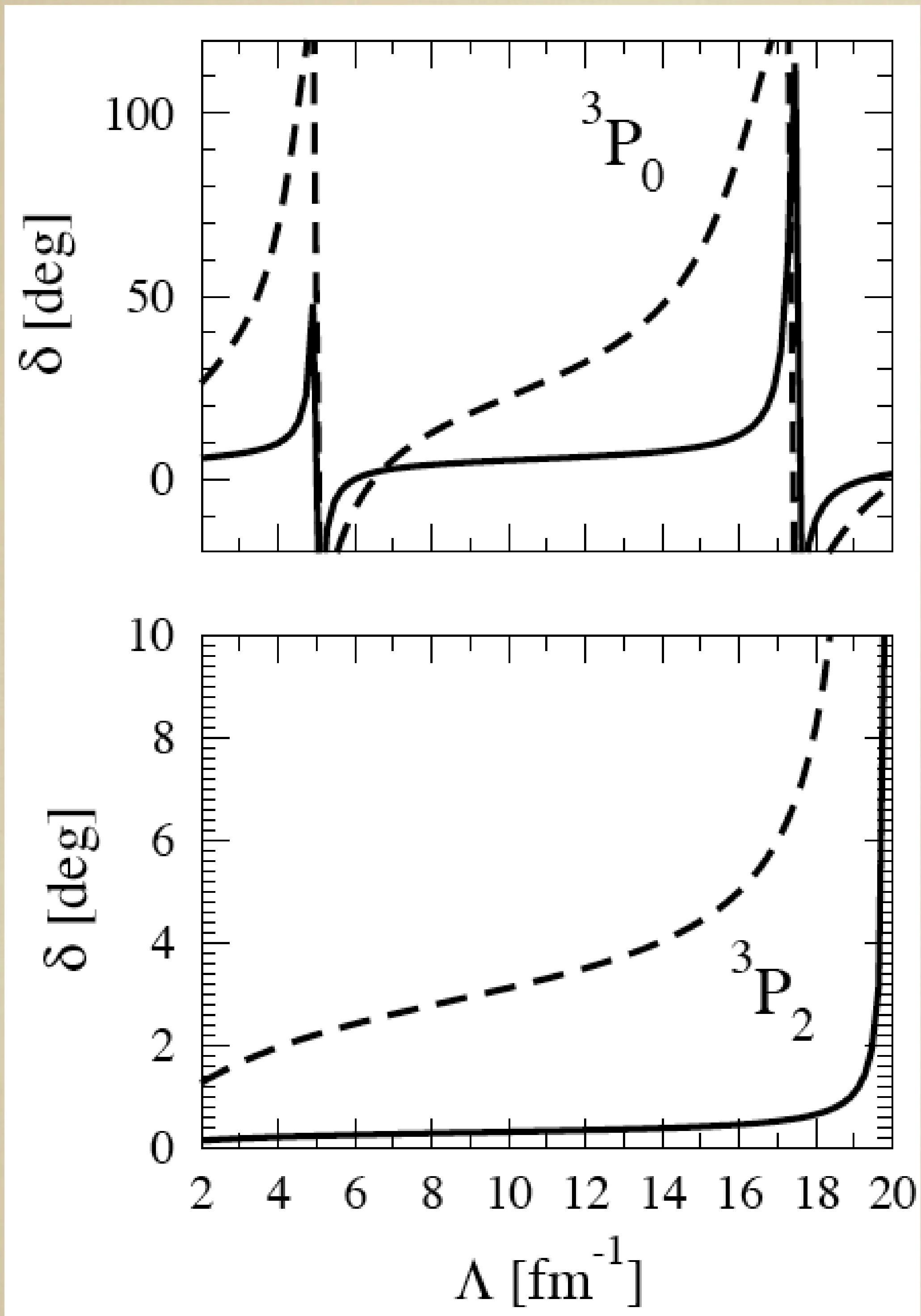

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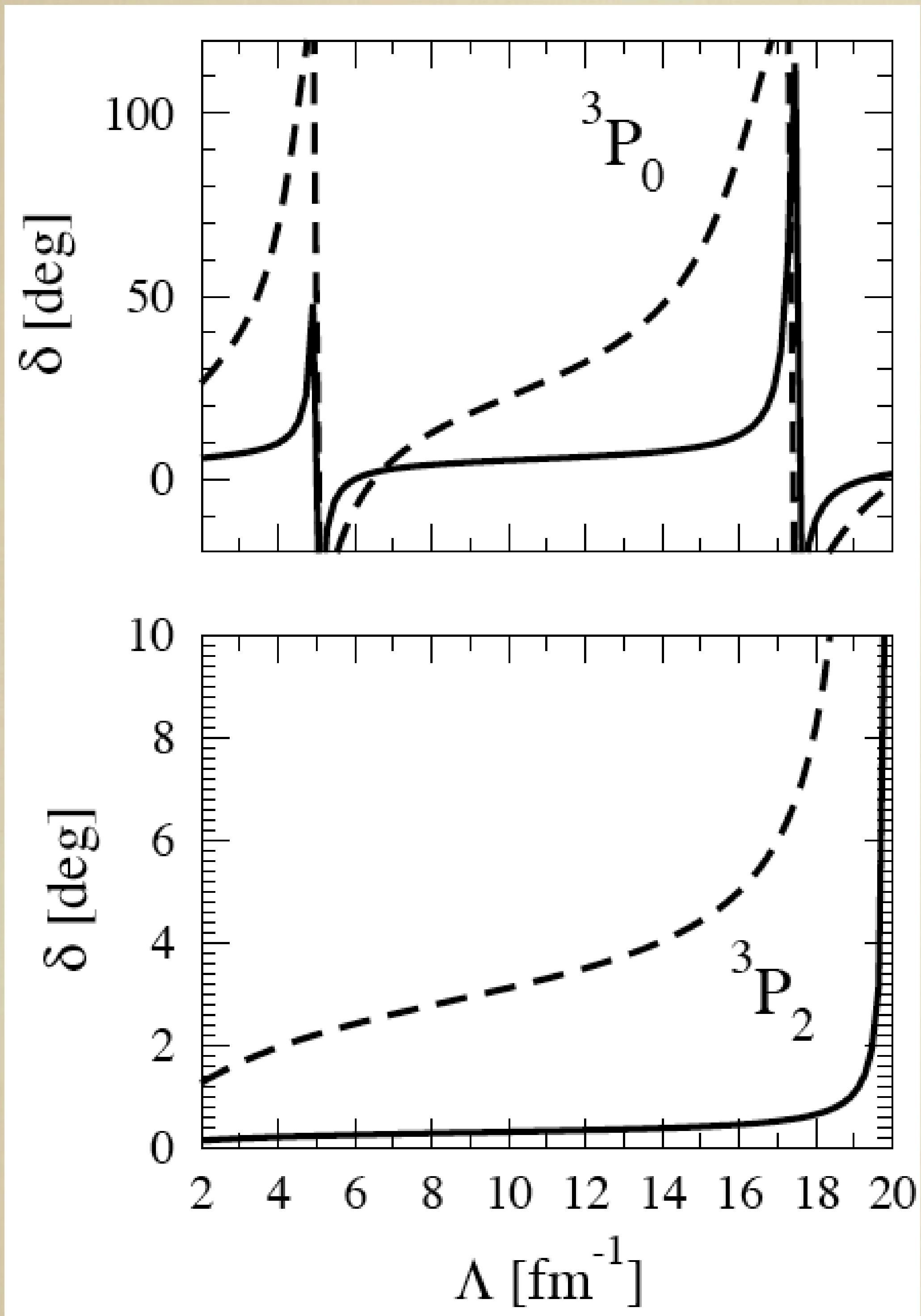
- “New leading order”: 1π exchange plus contact interactions, iterated, in 3S1, 3P0 and 3P2

- Meanwhile: 1π exchange, iterated, in 3P1; contact interaction, iterated, in 1S0.

The quest V: power counting



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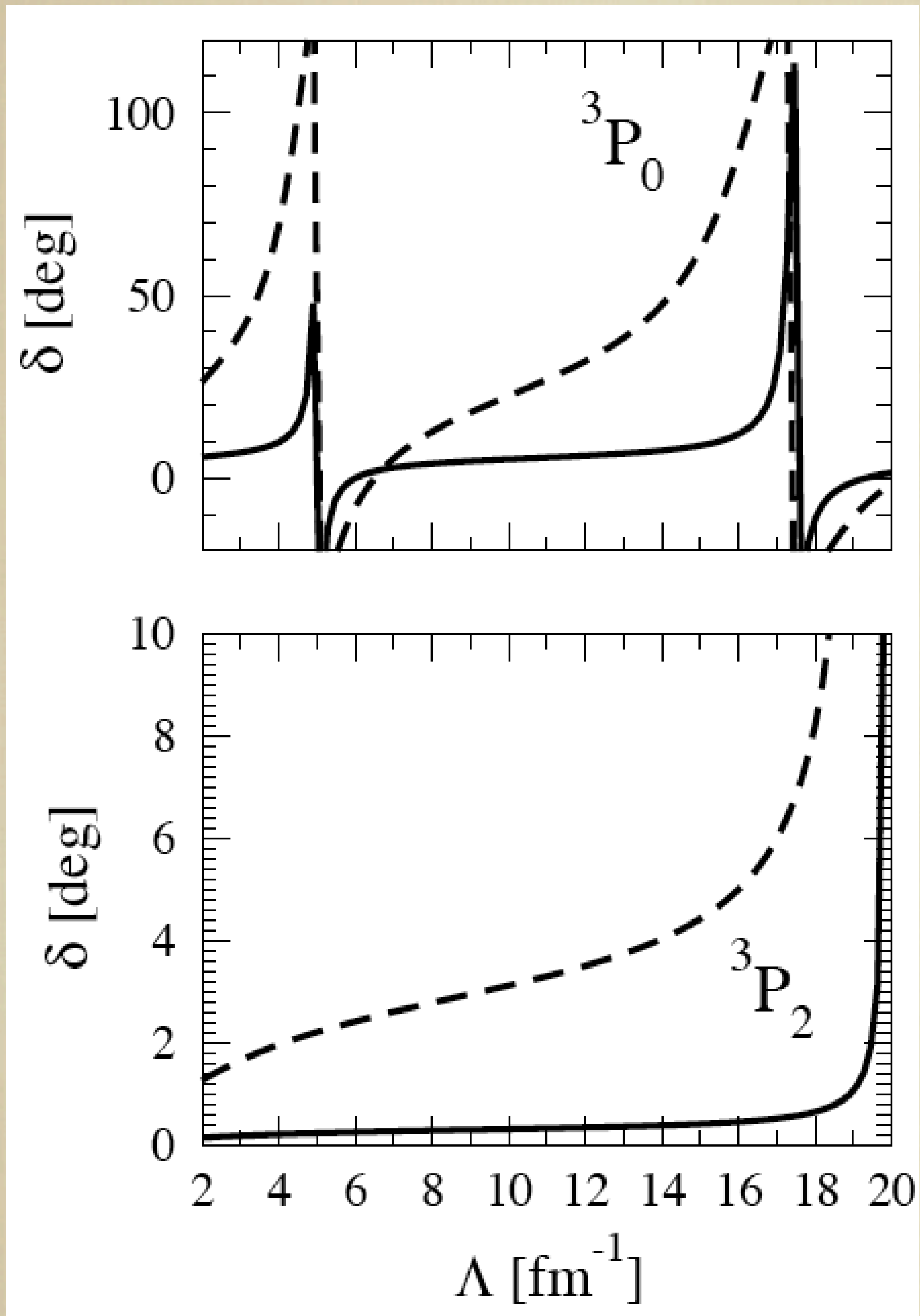

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Moral: NDA doesn't predict scaling of short-distance operators needed for renormalization if LO wave functions are not plane waves

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- Make one-pion exchange softer, by introducing a Pauli-Villars regulator. Keep regulator mass finite

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- Can even make it soft enough that it appears perturbative.

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- Argue that cutoff should never get above m_ρ Epelbaum, Meissner (2006)

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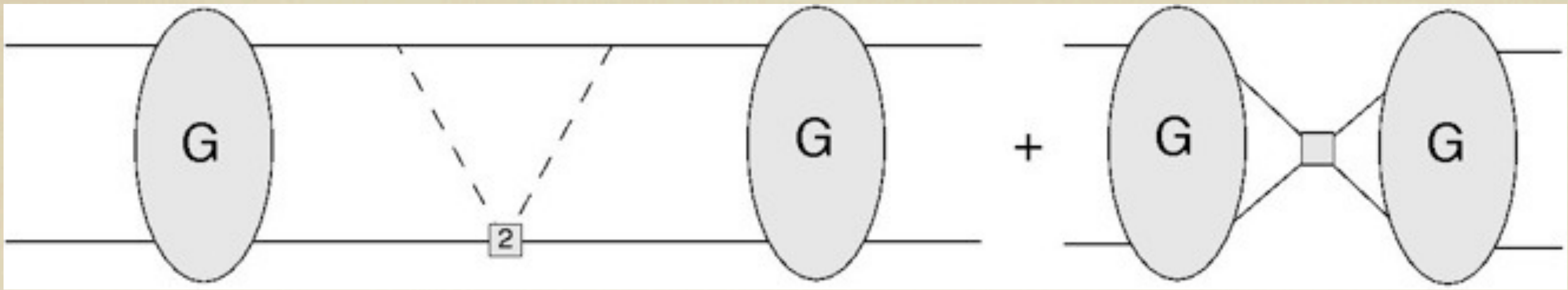
- Analysis tool: co-ordinate space matrix elements of $V^{(3)}$ (say) between $|\psi^{(0)}\rangle$
- Equivalent momentum-space formulation

An example: sub-leading TPE in 3S1

$$\frac{d}{dr_c}$$



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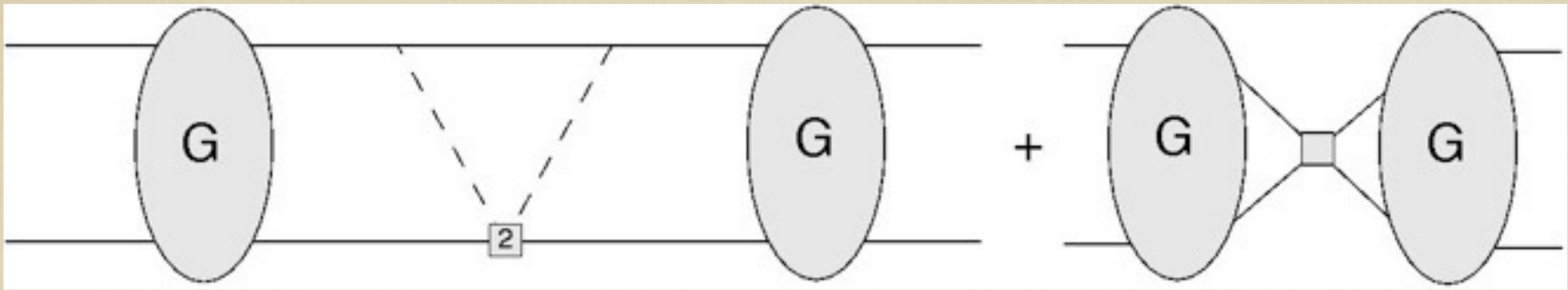

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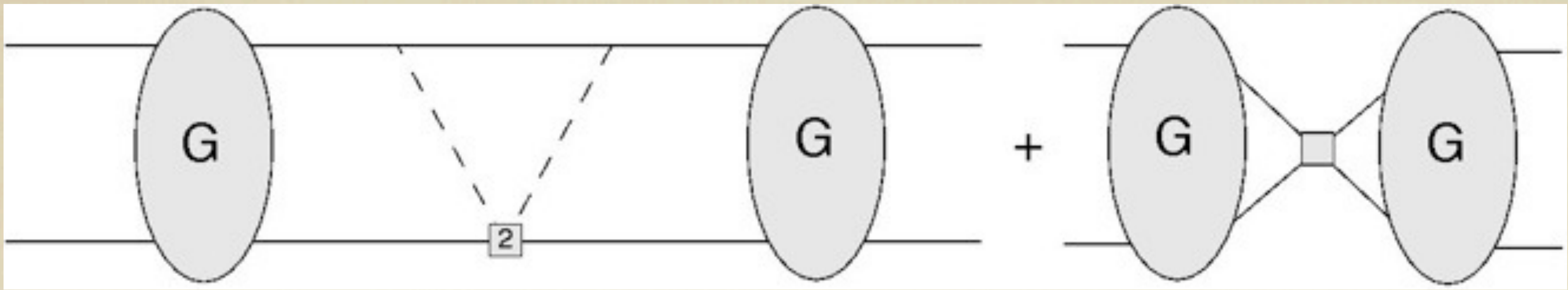

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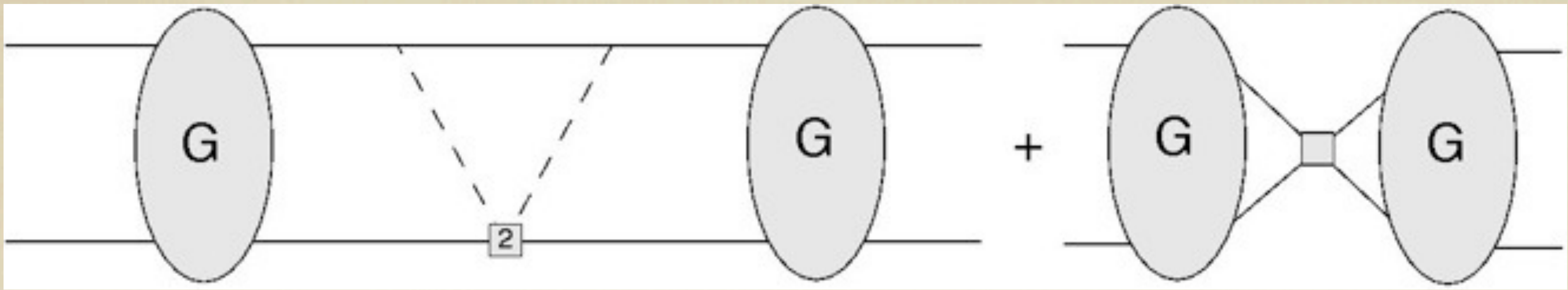

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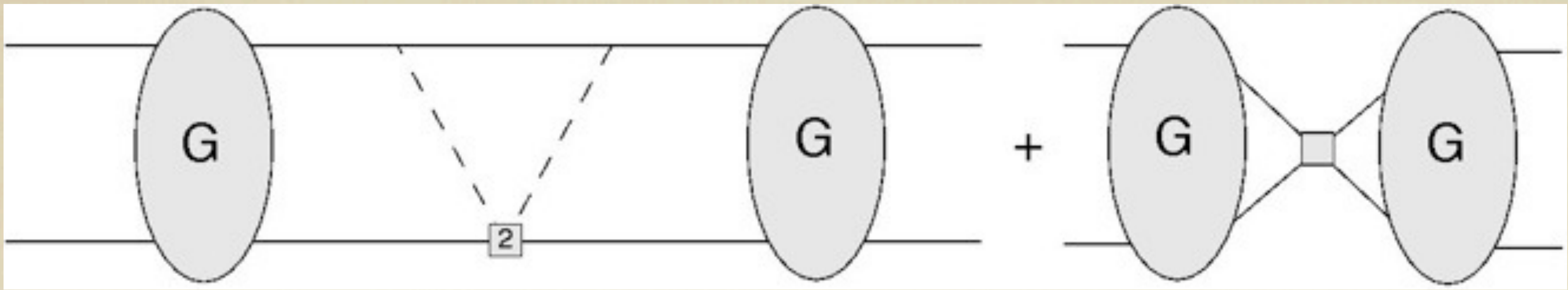

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- Real difference in P waves, where $\sim r^2$ gets replaced by $\sim r^{3/4}$

Birse (2006)

- Two NN contact interactions needed to renormalize $V^{(3)}$ in attractive triplet P waves

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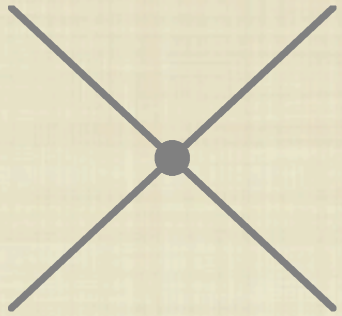
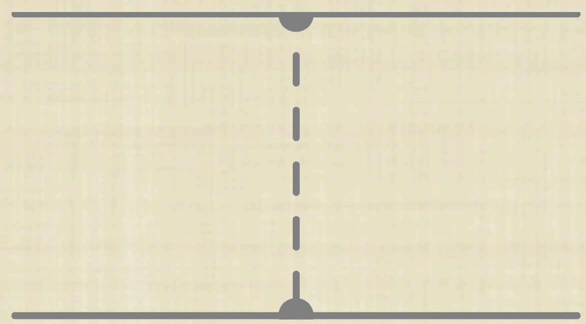
$V^{(0)} =$  $+$  ;

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- Since deuteron is also fine-tuned there is a similar (but not the same!) enhancement of contact interactions in the 3S1 channel

Birse (2009)

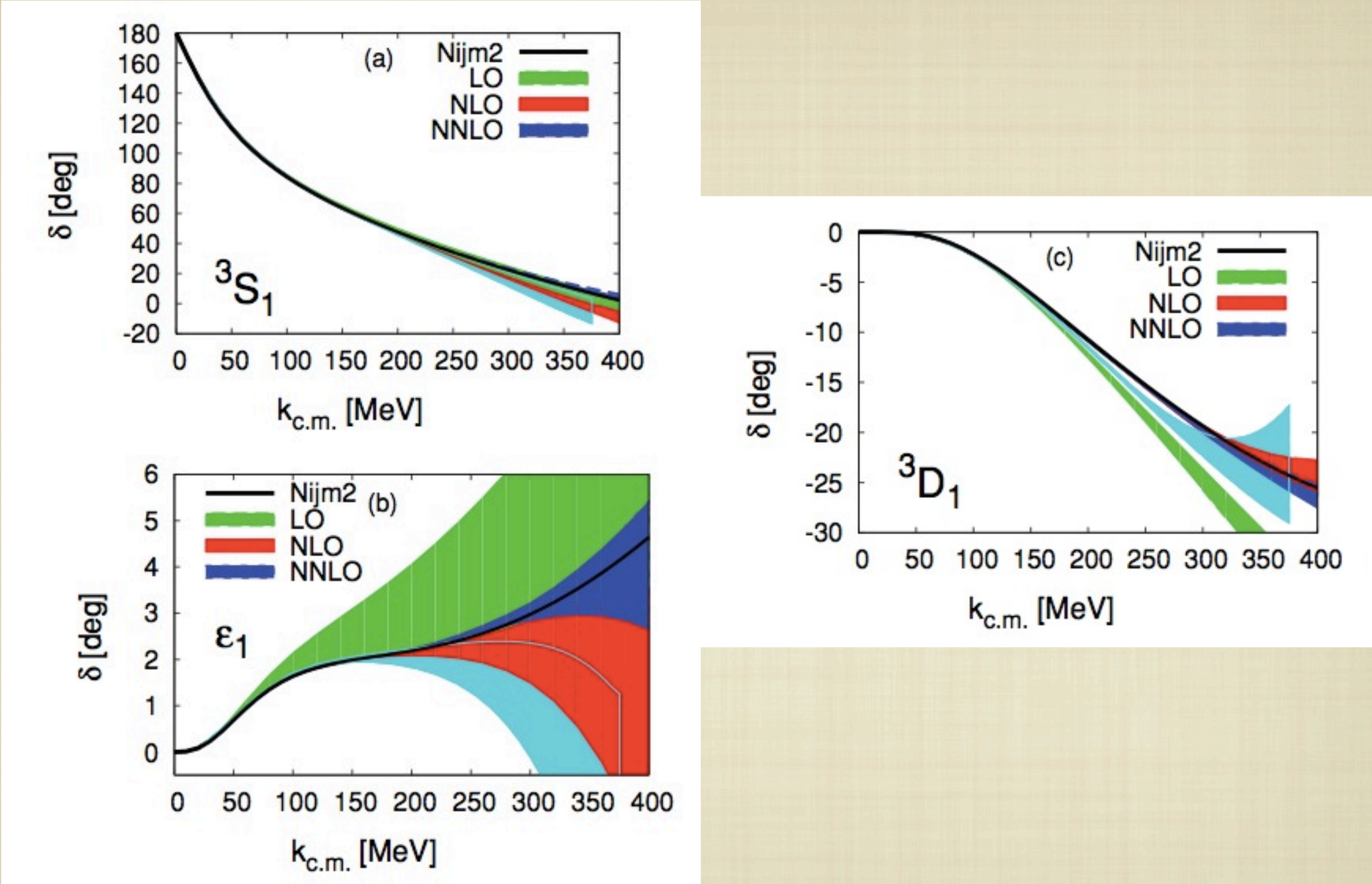
Summary of results I

Birse (2009)

ORDER	INCLUDED
P^{-1}	C^{1S0}, C^{3S1}, 1π exchange
$P^{-1/2}$	C^{3P0}, C^{3P2}
P^{0}	C_2^{1S0}
$P^{1/2}$	C_2^{3S1}
$P^{3/2}$	C_2^{3P0}, C_2^{3P2}
P^{2}	Renormalized leading 2π exchange, C^{1P1}, C^{3P1}, C_4^{1S0}, $C^{\varepsilon 1}$
$P^{5/2}$	C_4^{3S1}
P^{3}	Renormalized sub-leading 2π exchange

Summary of results III

Pavon Valderrama (2011-12)



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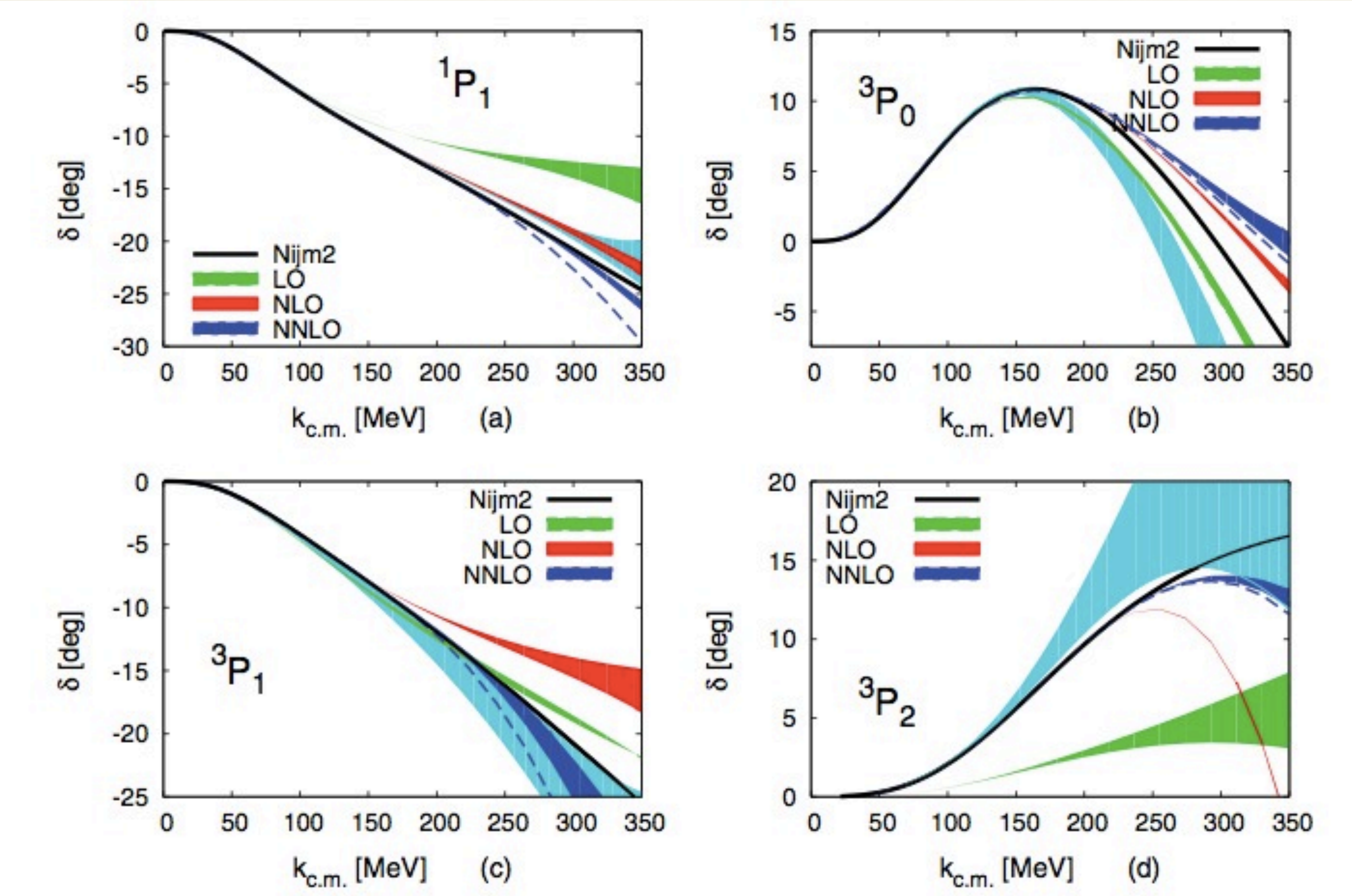
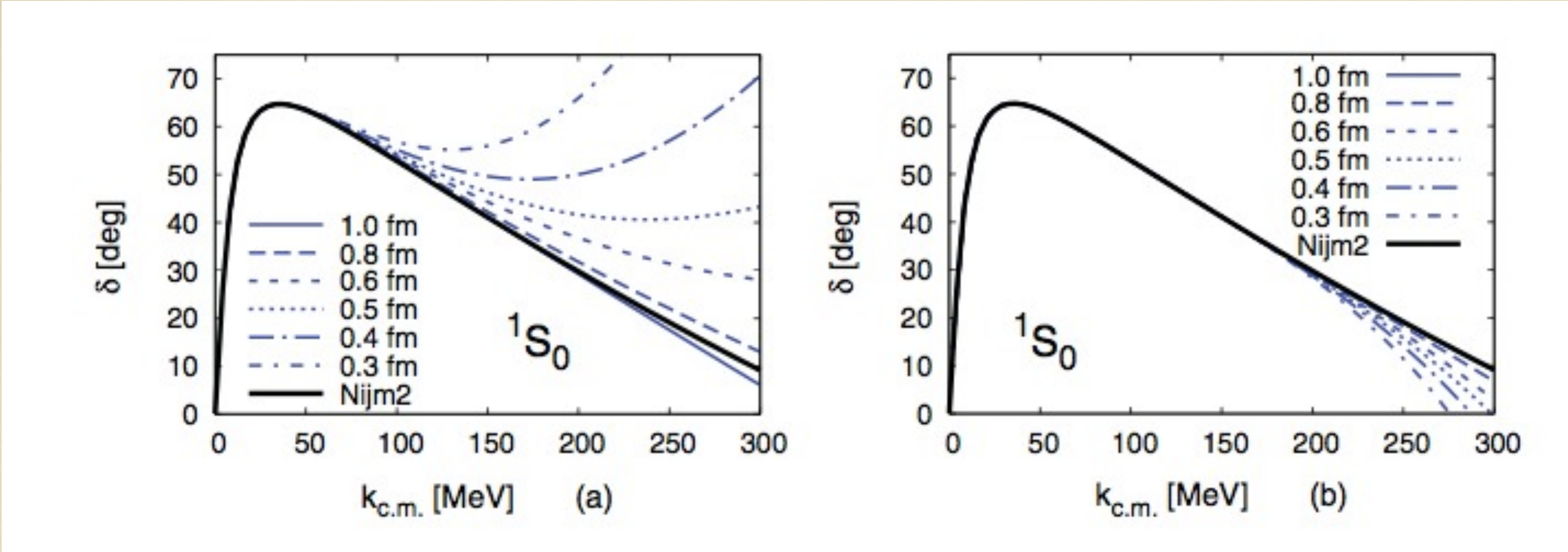


r_c dependence in "Weinberg" approach not under control in, e.g., $^3P_0$

Summary of results IV: $^1S_0$ phases



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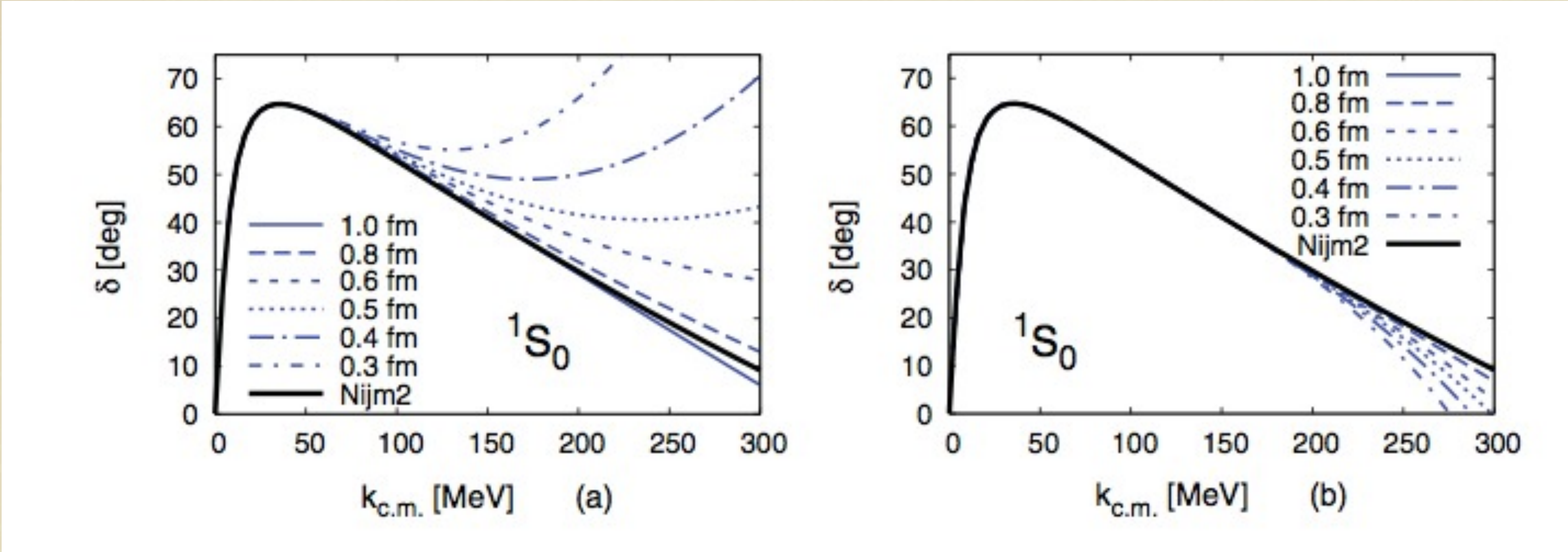

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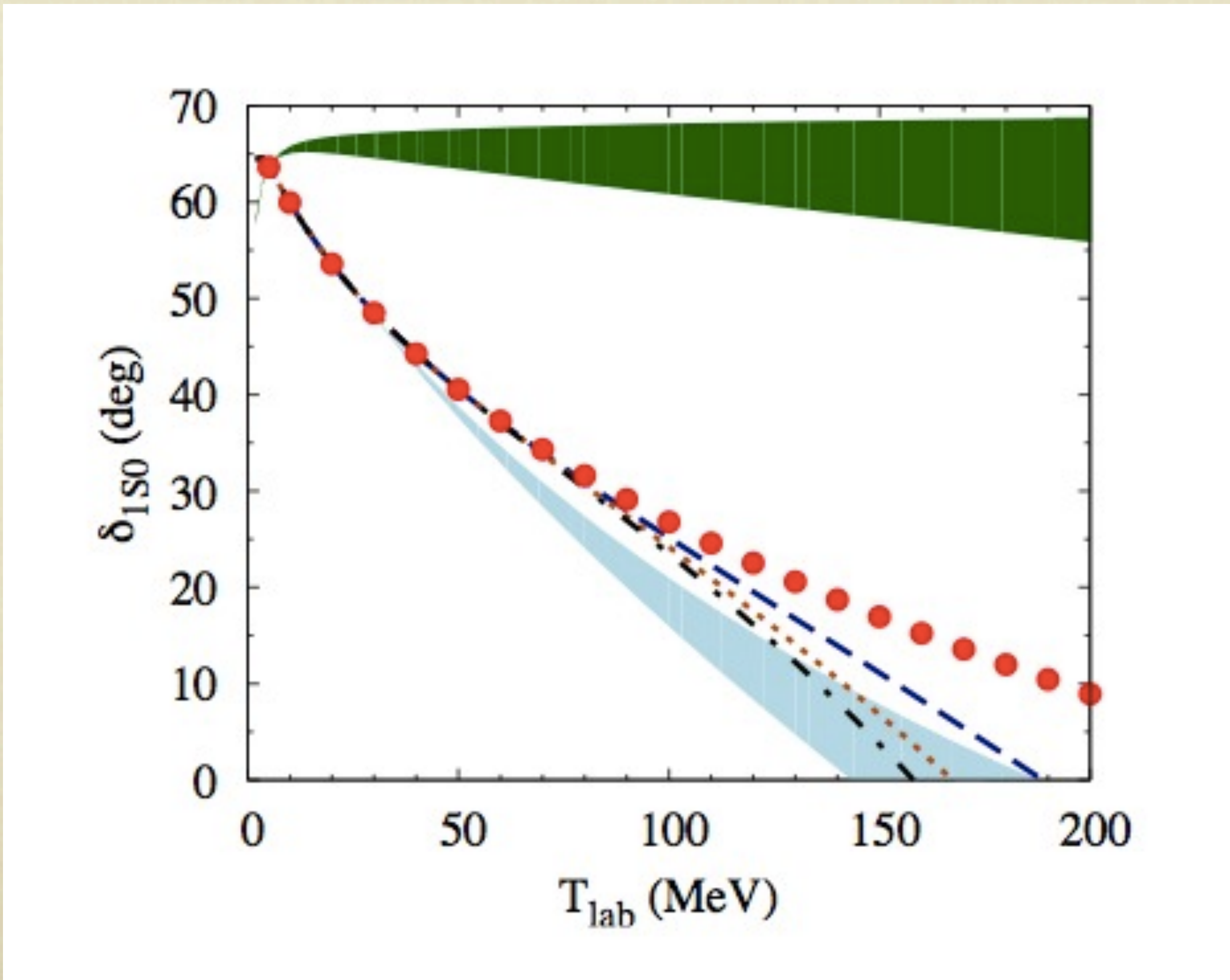

Long and Yang (2012)

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- Disagreement about counting for waves where one-pion exchange is repulsive (e.g. $^3P_1$); number of counterterms needed to stabilize $^3P_2$-$^3F_2$
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Baru, Epelbaum, Hanhart, Hoferichter, Kudratsyev, DP (2012)

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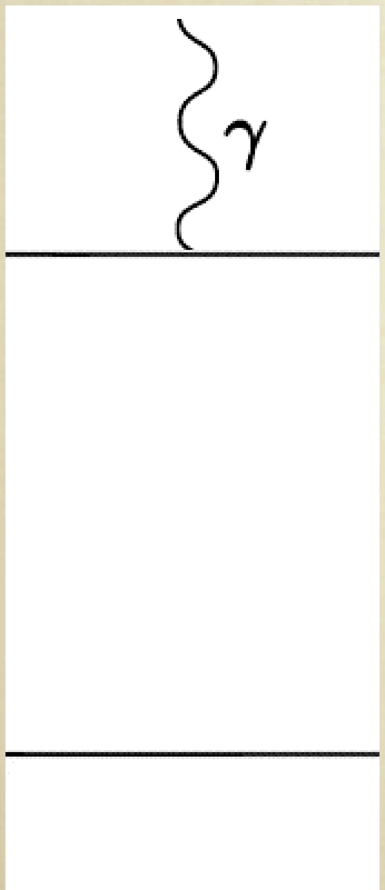

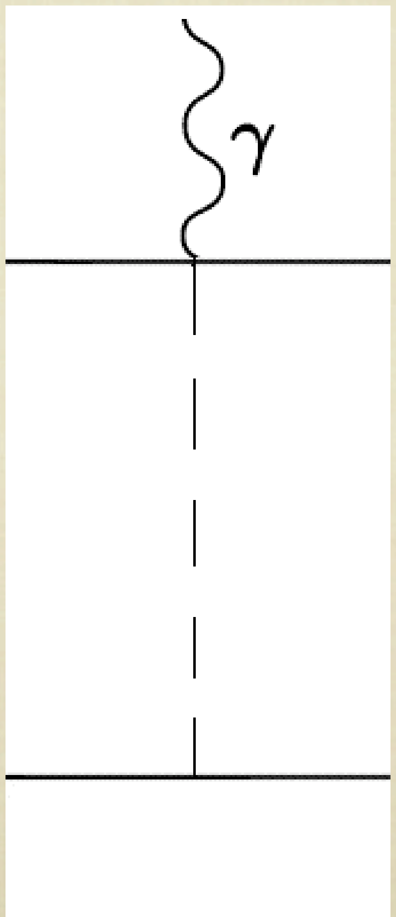

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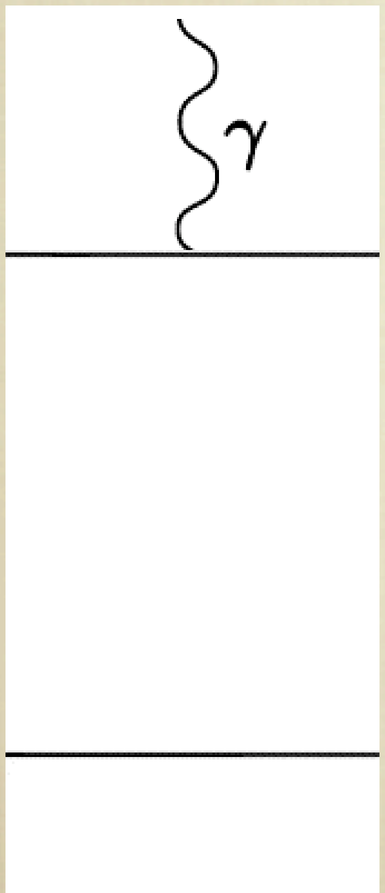

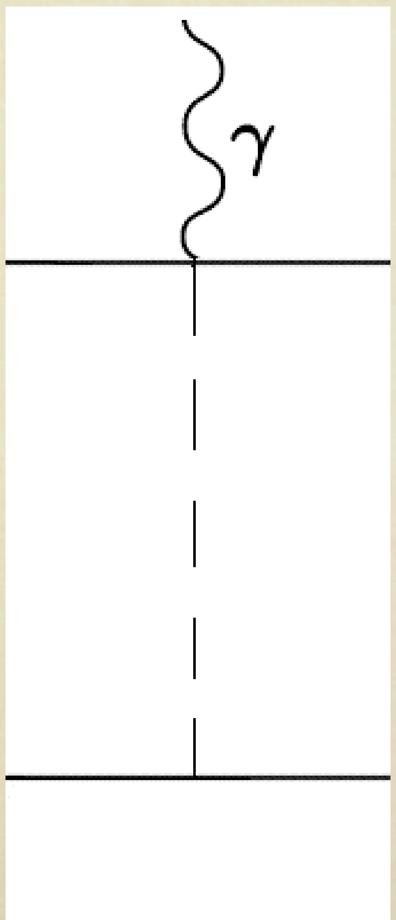

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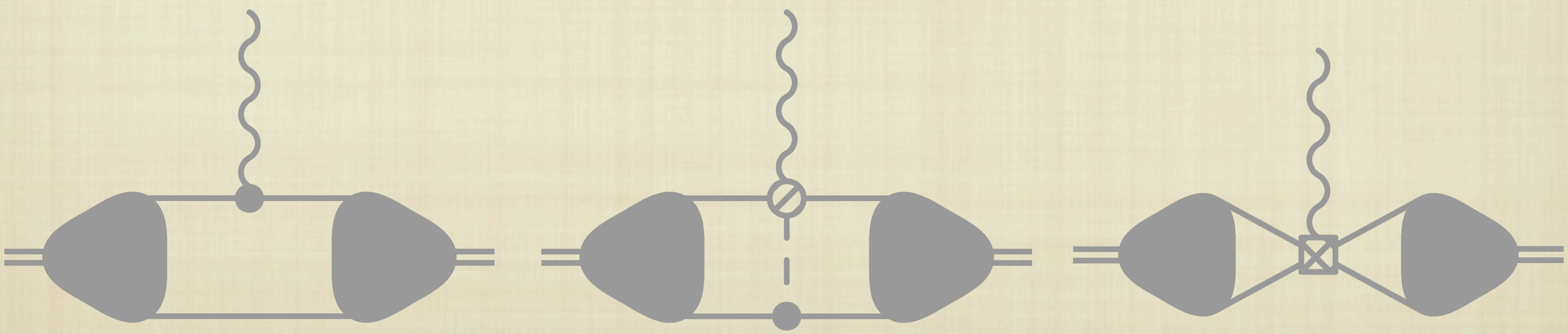
SUPPRESSED BY $1/M_N$ Phillips (2003)



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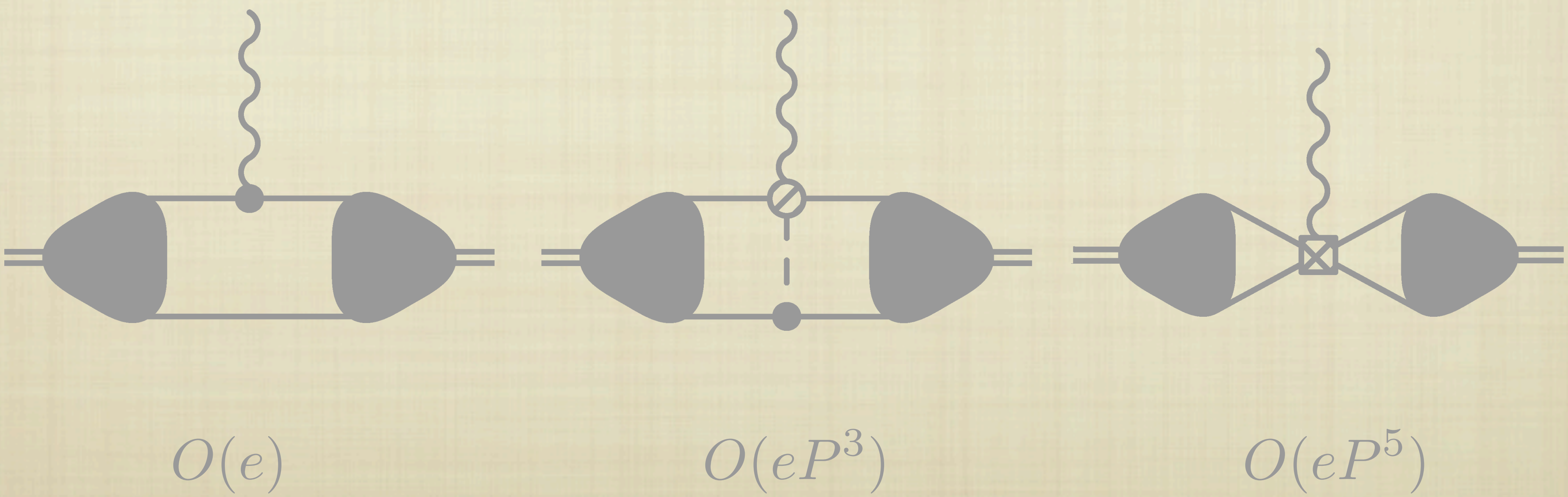

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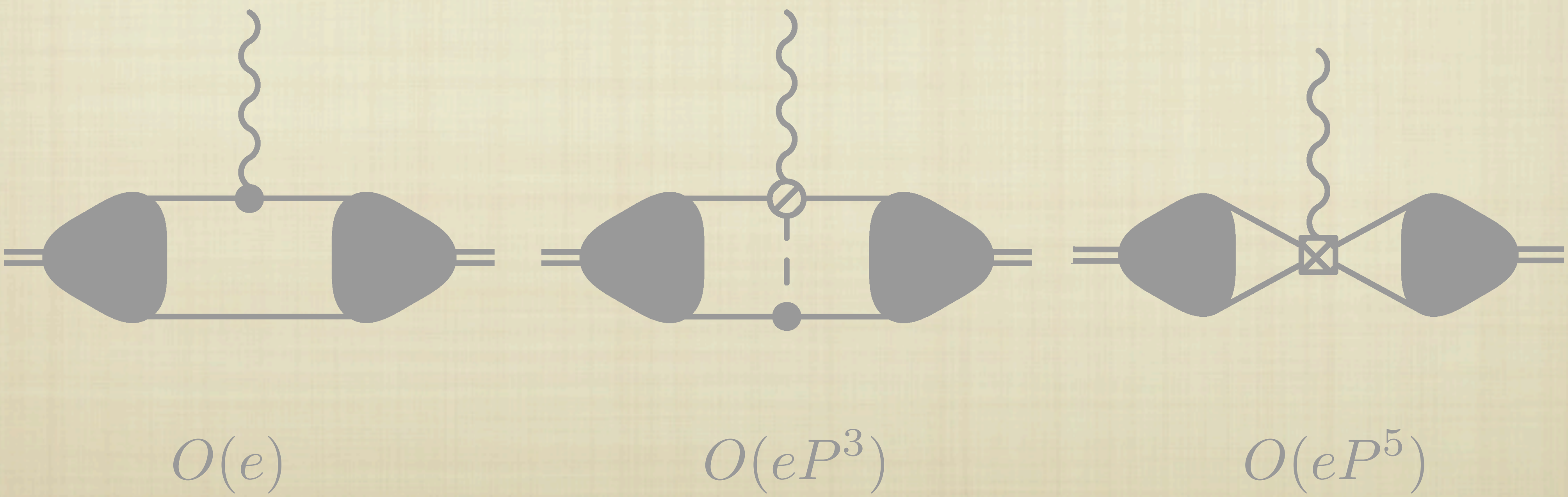
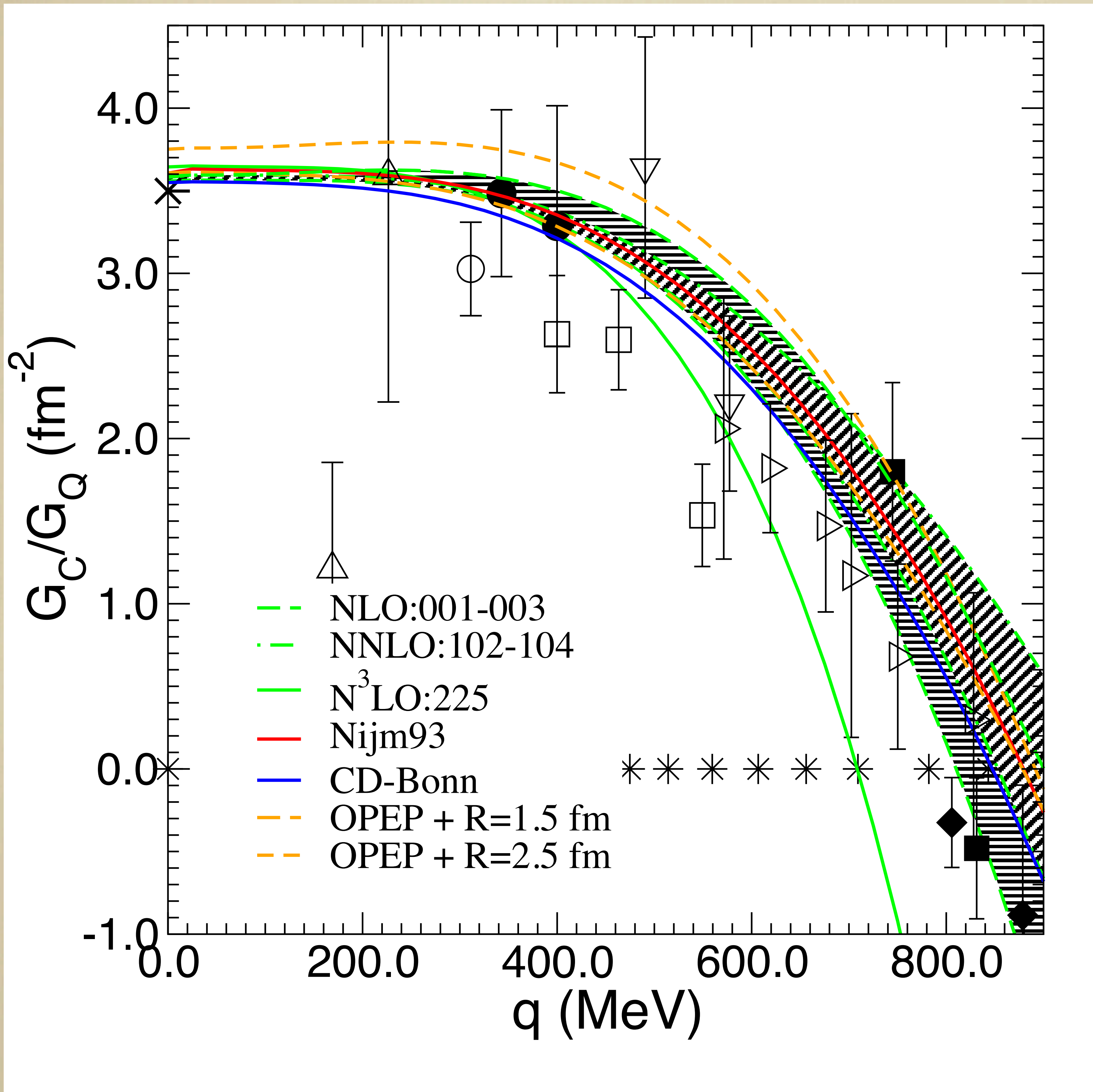
IN NDA COUNTING FOR SHORT-DISTANCE OPERATORS



Renormalizing G_C/G_Q

Phillips (2007)



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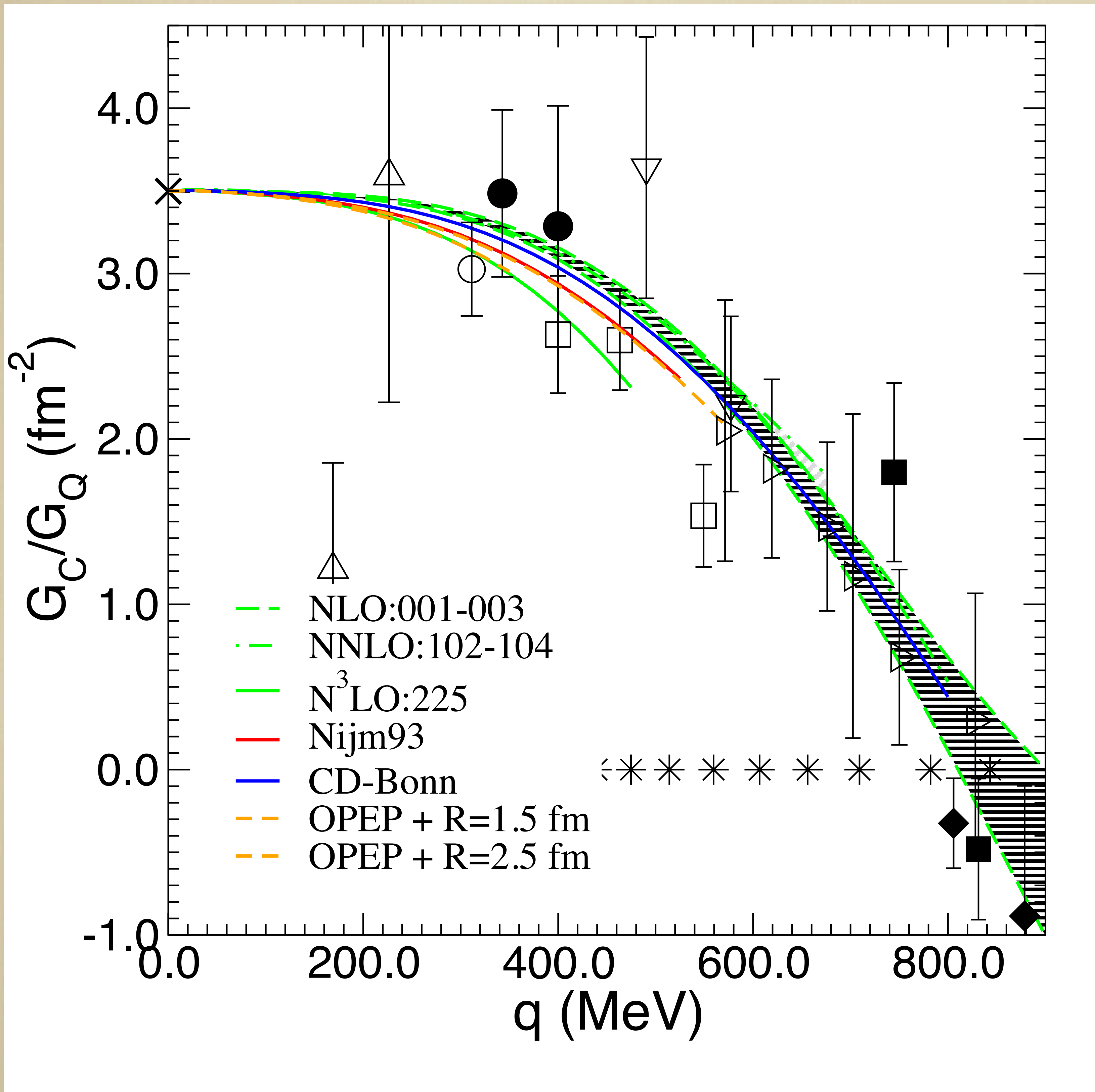

- Adjust $O(eP^5)$ contact term to reproduce Q_d
- Ratio is largely independent of model for q<600 MeV
- G_C/G_Q to 3% at Q= 0.39 GeV

Confronting experiment

Zhang et al., PRL (2011)

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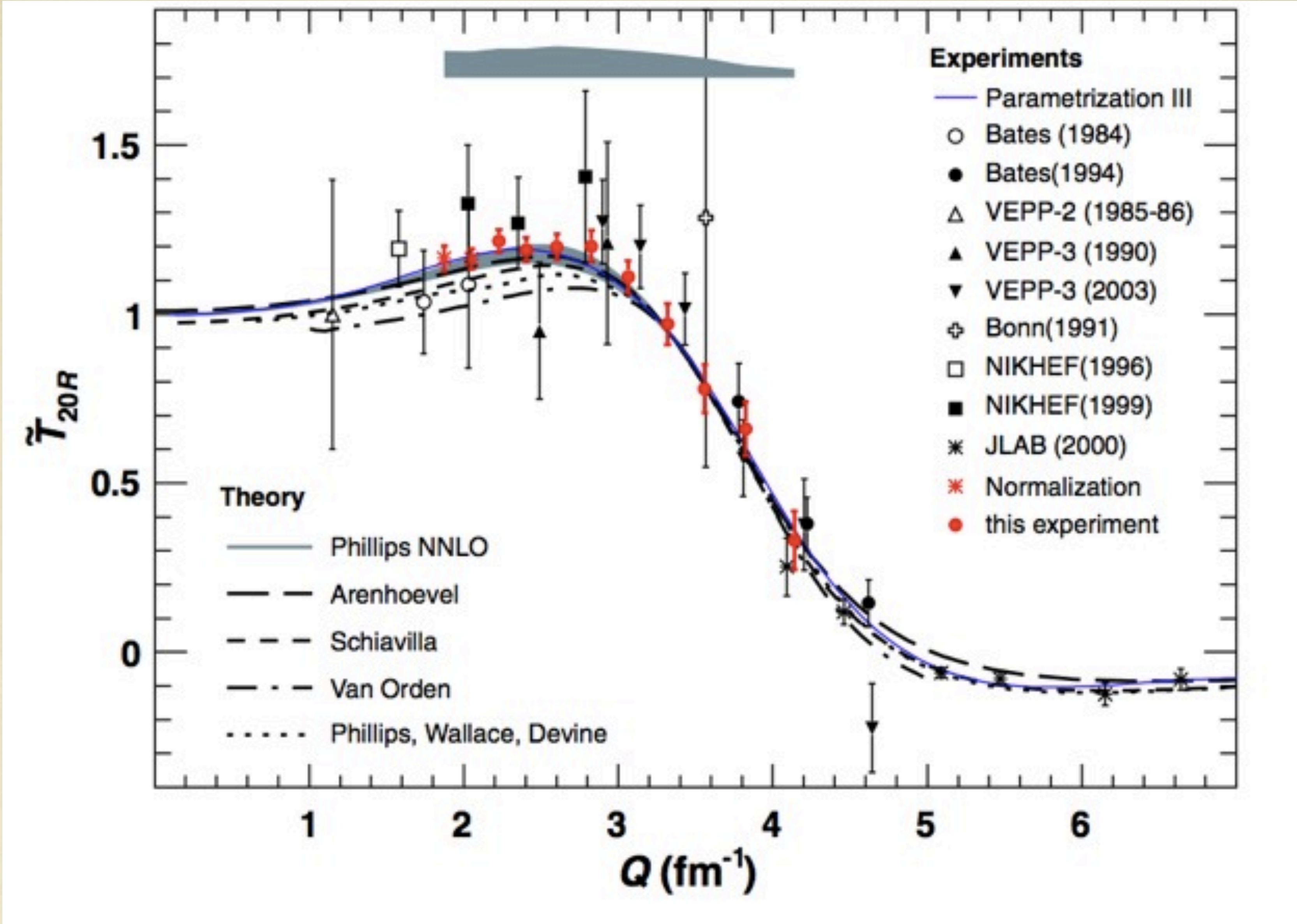

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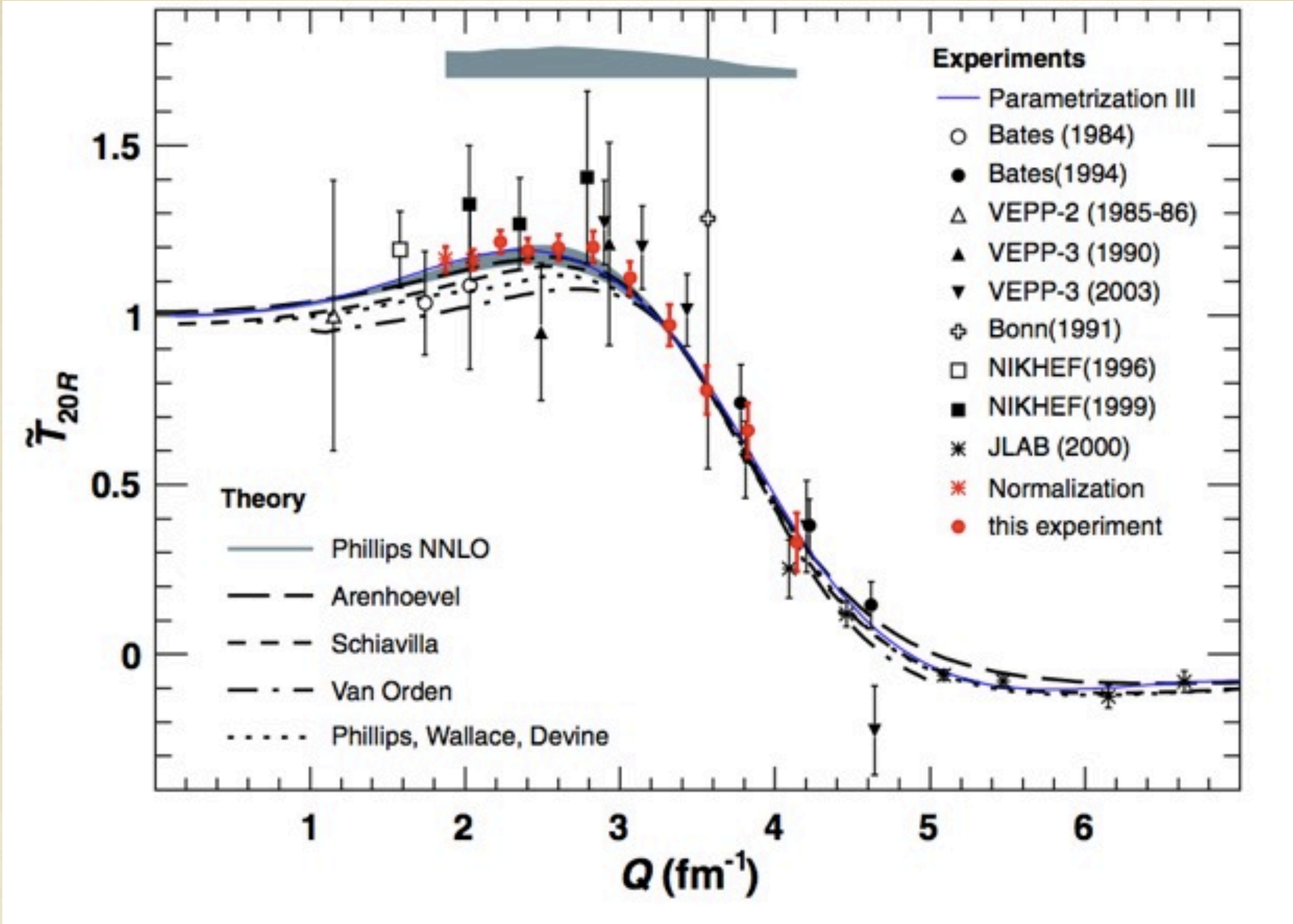
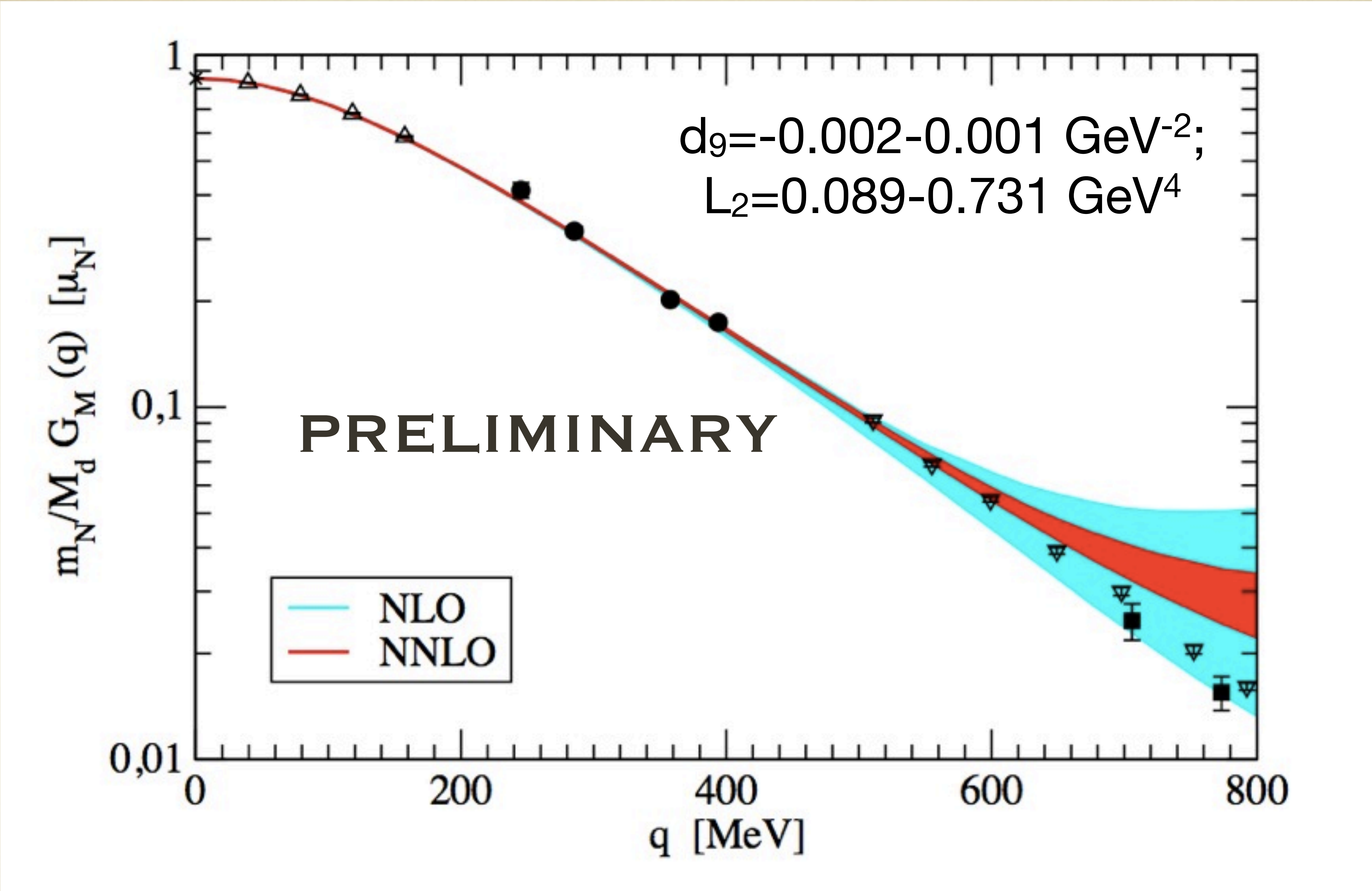


- Prediction for $G_C \leftrightarrow A$ at low Q^2: Hall A experiment

Yang, Kaiser, Park, Phillips (in preparation)

- Application to f_L in (e,e'p)

G_M to same order



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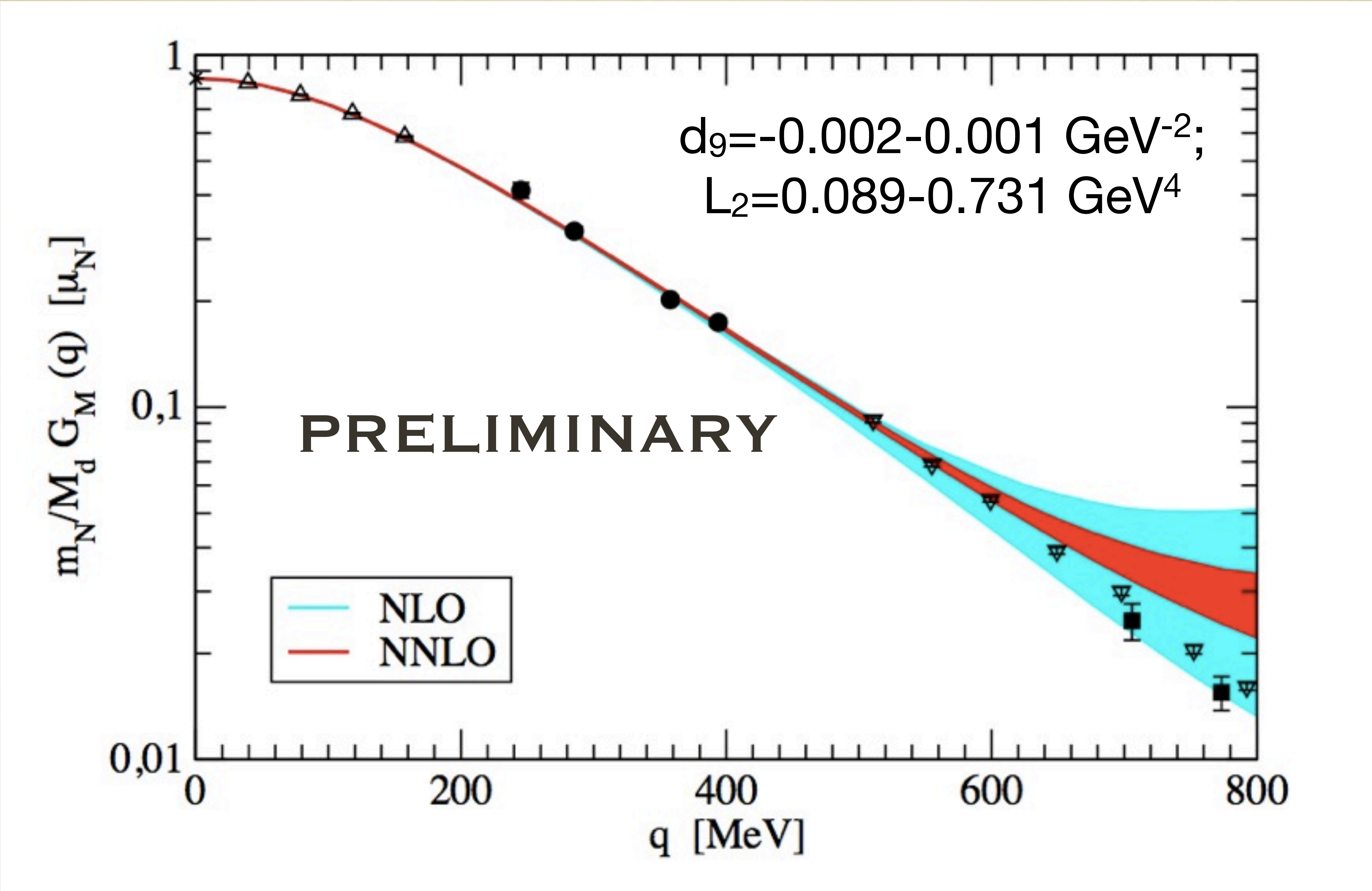

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- Application of electroweak operators in A=3,... ongoing

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- Threshold M1 capture; talk of L. Girlanda

- Weak capture on deuterium: Γ_D=399(3) s^{-1} in a χEFT calculation up to $O(P^3)$; talk of P. Kammel

  Marcucci et al., Phys. Rev. Lett. (2012)

- Application of electroweak operators in A=3,... ongoing

- Role of Δ(1232) in long-range part of V, electroweak operators

Building a better chiral V_{NN}

Building a better chiral V_{NN}

- Three-pion exchange less important than several short-distance operators

- For V_{NN} accurate to P^4 relative to leading include everything in "chiral potential" at NNLO plus second contact operators in $^3P_0$ and $^3P_2$, third in $^3S_1$ and $^1S_0$, and (?) 2 in $^3D_2$

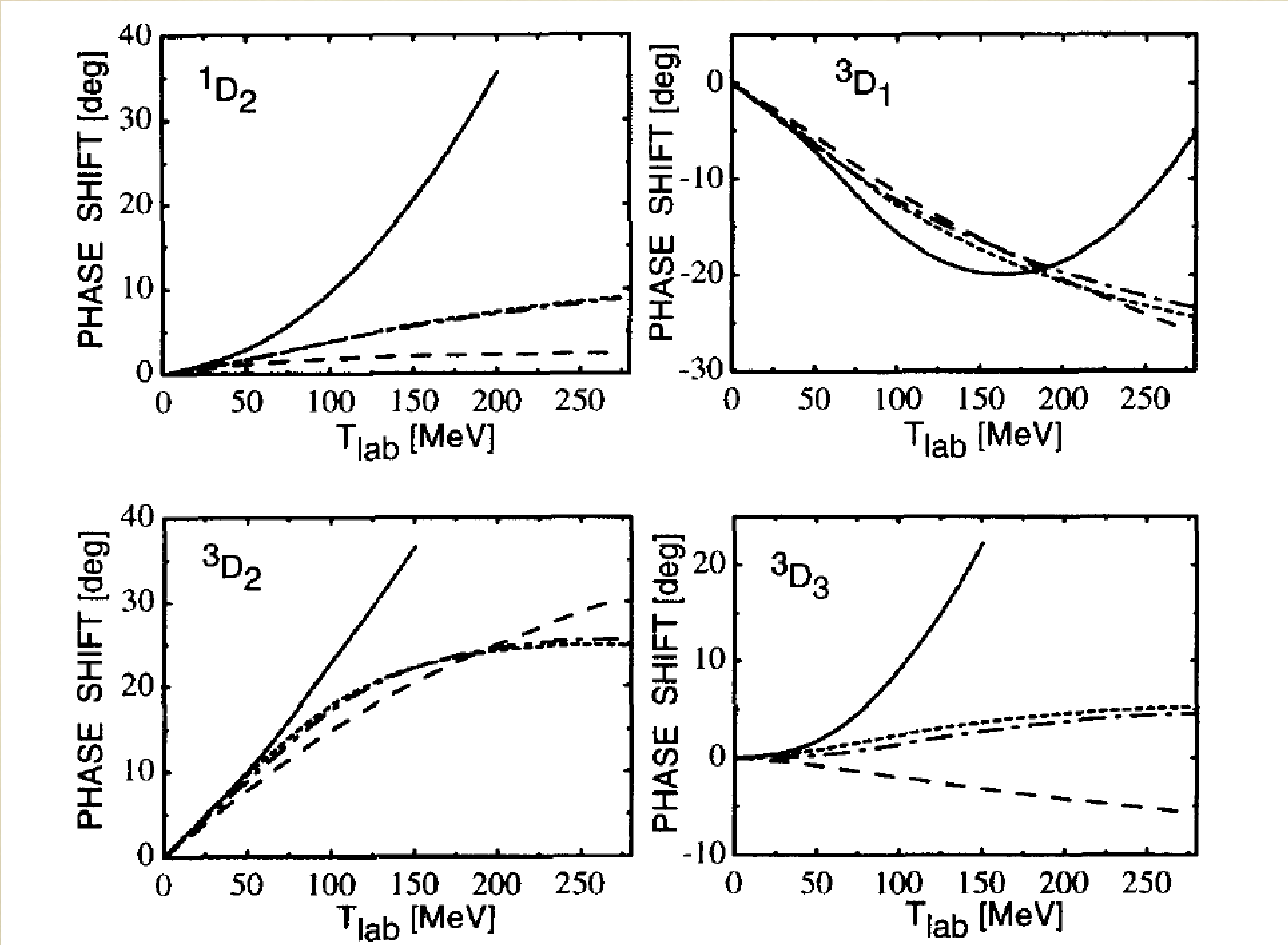
- Most of these additional pieces are in N^3LO potential

- C.f. Nijmegen phase-shift analysis: chiral two-pion exchange plus similar number of short-distance operators

- Real problems with counting may come in 3NF: more short-distance operators enter if this counting is correct

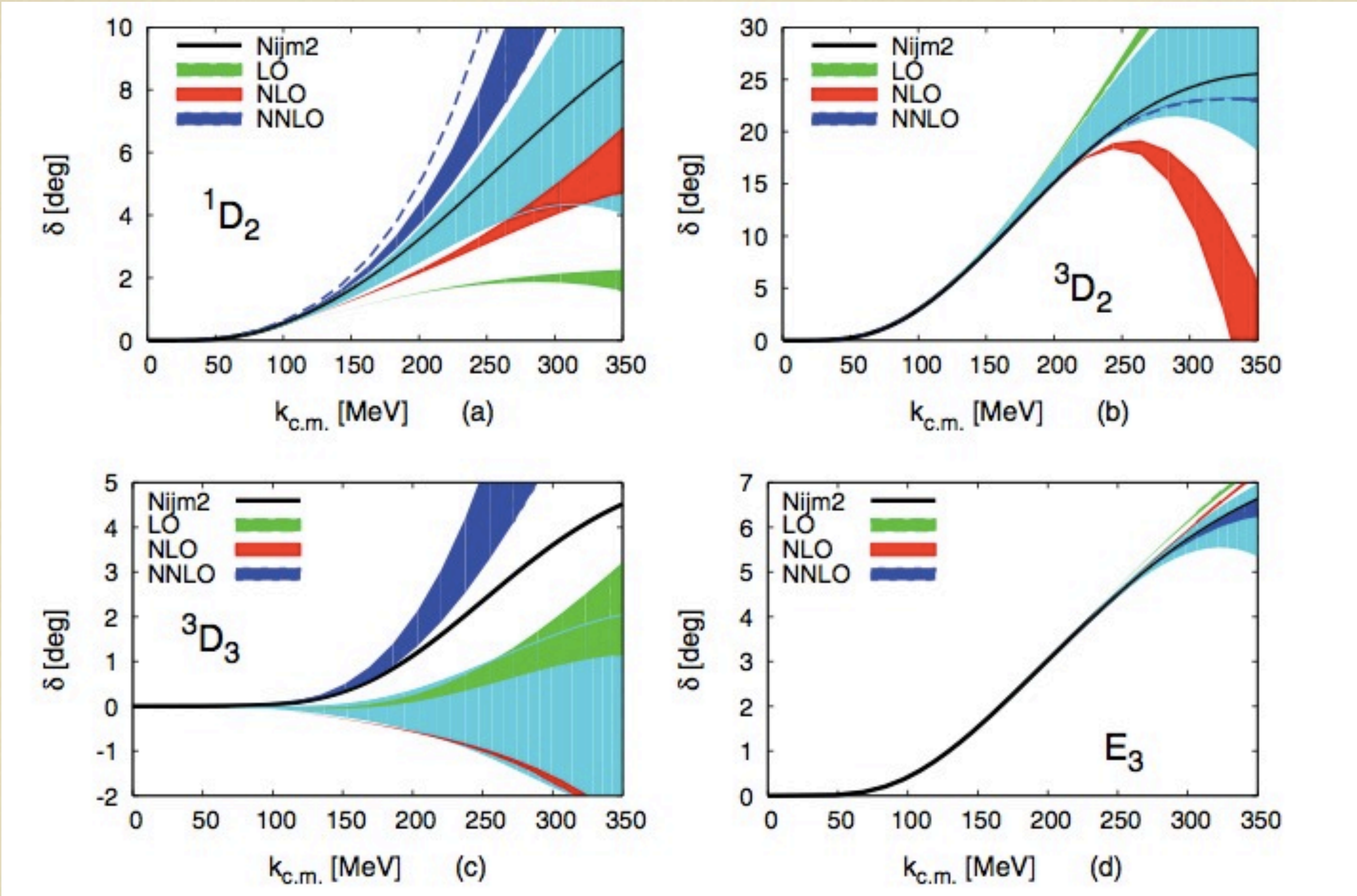
BACKUP SLIDES

D Waves



$^1D_2$
$^3D_1$
$^3D_2$
$^3D_3$
PHASE SHIFT [deg]
T_{lab} [MeV]
0
50
100
150
200
250
40
30
20
10
0
-10
-20
-30

Supplementary phase-shift plots



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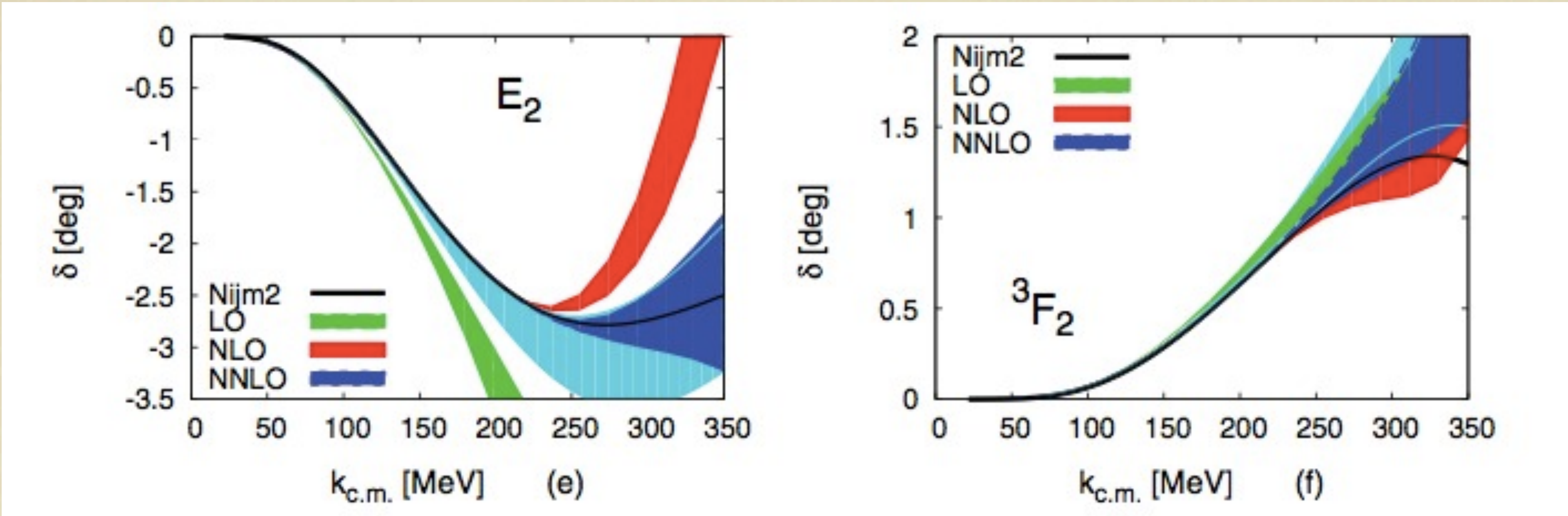
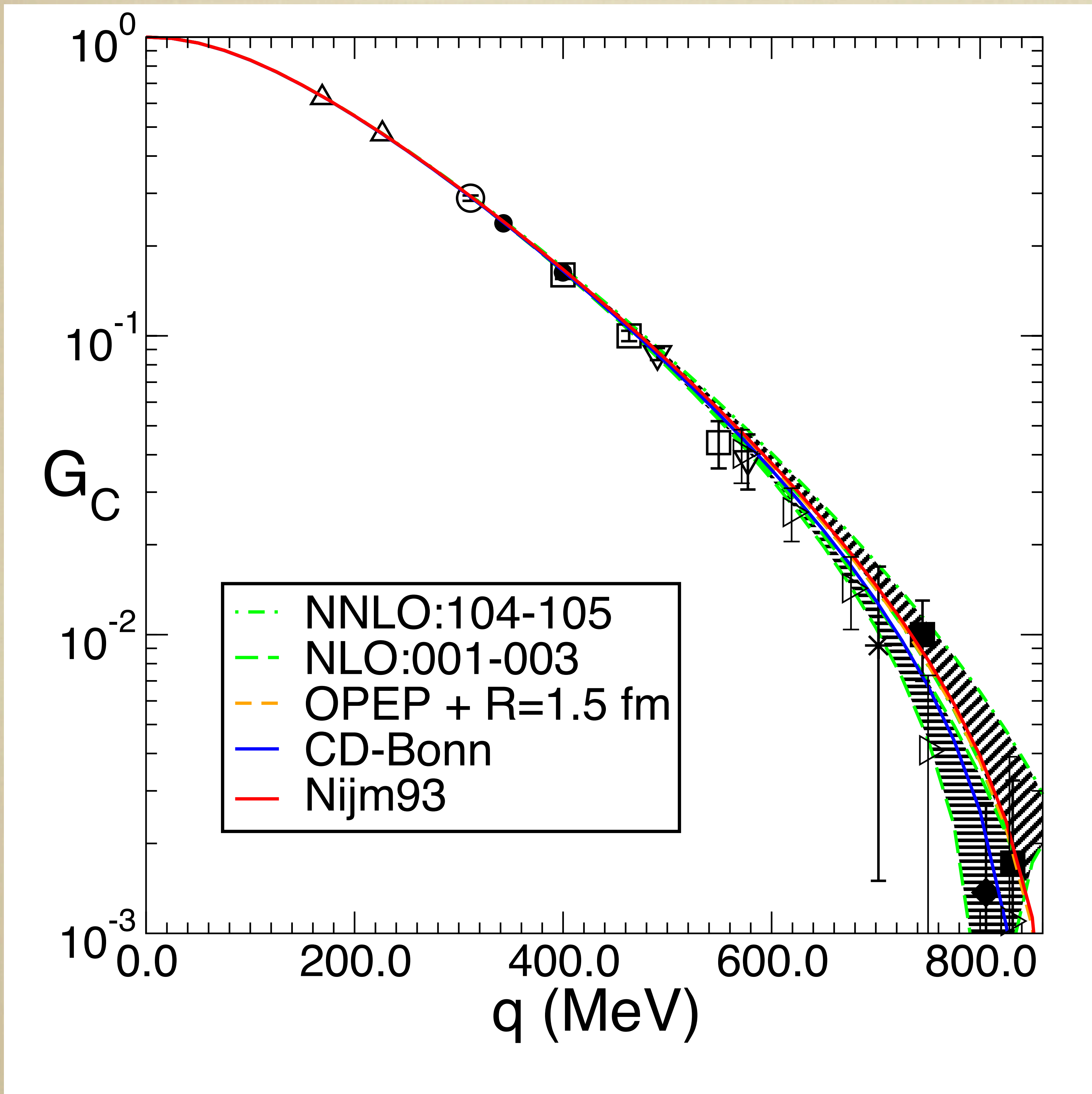


χEFT for G_C up to $O(eP^4)$



- Good J_0 convergence
- G_C dominated by $r \sim 1/m_\pi$ physics in this q range
- But we need to constrain interplay of short-distance pieces of charge operator and pion-range physics

DP, J. Phys. G 34, 365 (2007)

Static properties and renormalization

Static properties and renormalization

	Expt.	NNLO	N^3LO	Nijm93
$<r_d^2>_{pt}$ (fm)	1.9753(10)	1.974-1.976	1.979-1.989	1.970
Q_d (fm^2)	0.2859(3)	0.279-0.282	0.264-0.268	0.276

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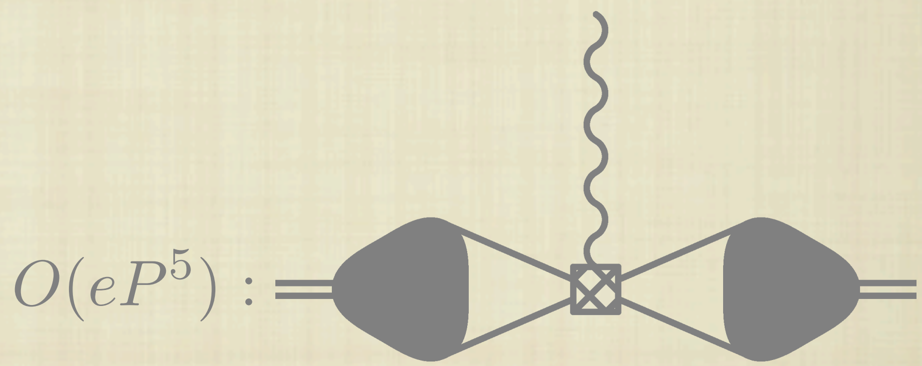
Two-body $^3S_1 \rightarrow {}^3S_1$ operator:



Chen, Rupak, and Savage (1999); DP (2007)

G_M beyond impulse approximation

	Expt.	NLO	NNLO	Nijm93
$\mu_d(\mu_N)$	0.857406(1)	0.856-0.862	0.853-0.860	0.848

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$$\mathbf{J}^{(s)}_{d_9} = -2e\frac{g_A i}{f_\pi^2} d_9 \tau_1^a \tau_2^a \frac{\sigma_2 \cdot \mathbf{q}_2}{\mathbf{q}_2^2 + m_\pi^2}(\mathbf{q}_2 \times \mathbf{q}) + (1 \leftrightarrow 2)$$

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- d_9 poorly constrained from single-nucleon sector