New ideas in the EFT approach to nuclear systems

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Svenskt kärnfysikermöte 2018

Uppsala

Oct/18/2018

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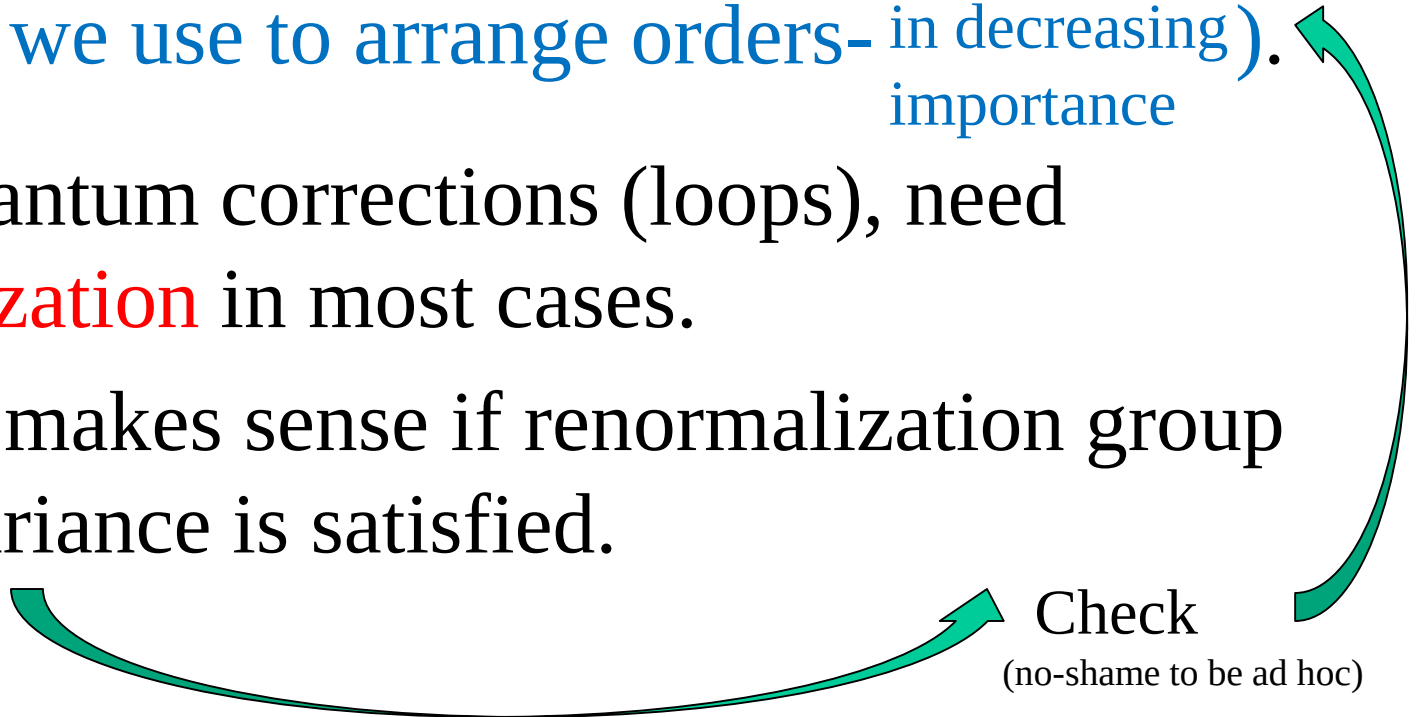
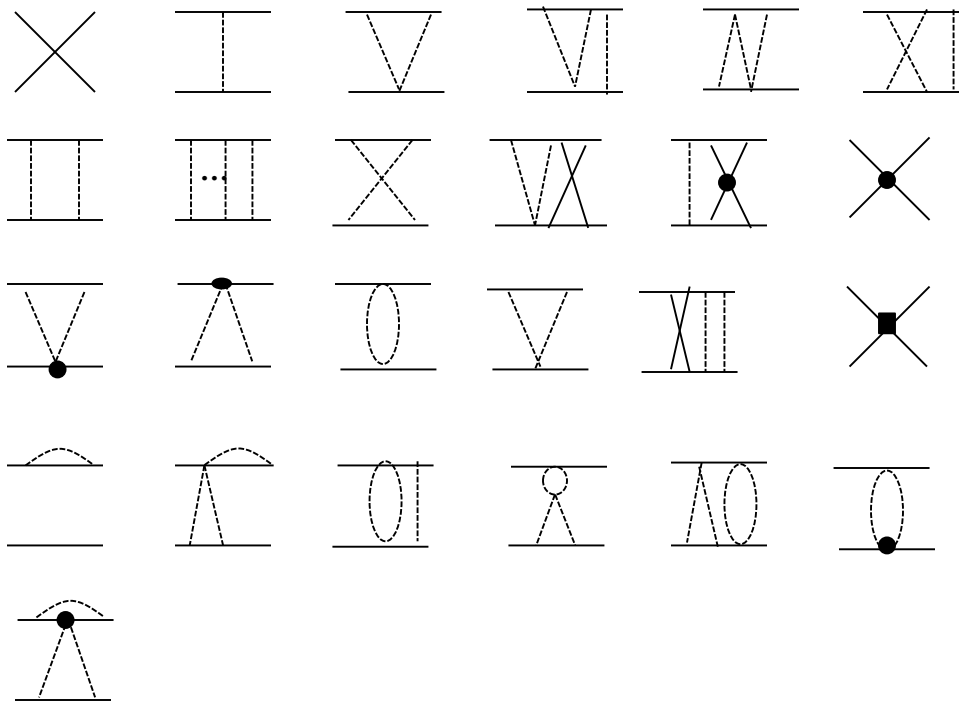
Effective field theory for the nuclear system

Effective field theory concepts

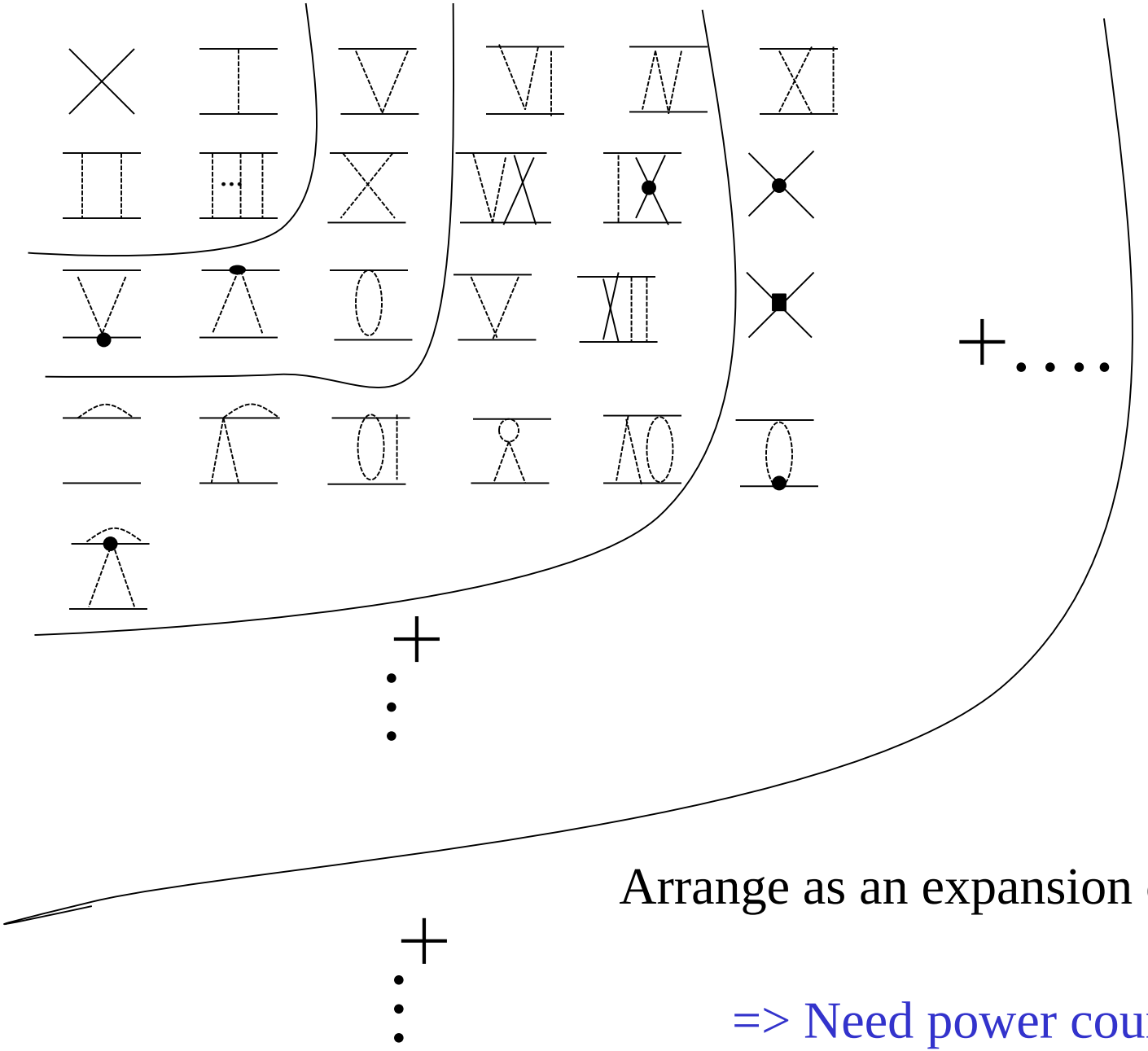
- Very complicated system, I know no details, only the symmetries of the system.
- Arrange the physics based on a separation of scales, then "figure out" the power counting (the thing we use to arrange orders- in decreasing importance).
- To get quantum corrections (loops), need renormalization in most cases.
- EFT only makes sense if renormalization group (RG) invariance is satisfied.



The Nuclear Force



Infinitely many diagrams.



Arrange as an expansion of $\Sigma_n (M_{lo}/M_{hi})^n$

=> Need power counting !

Conventional way: Weinberg's prescription

Epelbaum, Entem, Machleidt, Kaiser, Meissner, … etc., ~**90% of the people**

- **Arrange diagrams based on Weinberg's prescription:** each derivative on the terms in the Lagrangian is always suppressed by the underlying scale of chiral EFT, $M_{hi} \sim m_\sigma$.
- **Iterate the potential to all order (in L.S. or Schrodinger eq.), with an ultraviolet Λ.**

cutoff

Carried out to $N^4LO(Q^5/M^5_{hi})$

D. R. Entem, N. Kaiser, R. Machleidt and Y. Nosyk, PRC 92, 064001.
P. Reinert, H. Krebs and E. Epelbaum, arXiv:1711.08821.

$V(N^{n\geq 2}LO)$ performs as good as high accuracy $V_{CDBonn, AV18, etc.,\ldots}$, if we keep **$500<\Lambda<875$ MeV** (or, recently, **Λ=350~500** MeV).

Conventional power counting

Epelbaum, Entem, Machleidt, Kaiser, Meissner, … etc., ~**90% of the people**

Hope:

V LO NLO up to NNLO N3LO N4LO :

(one to one correspondence)

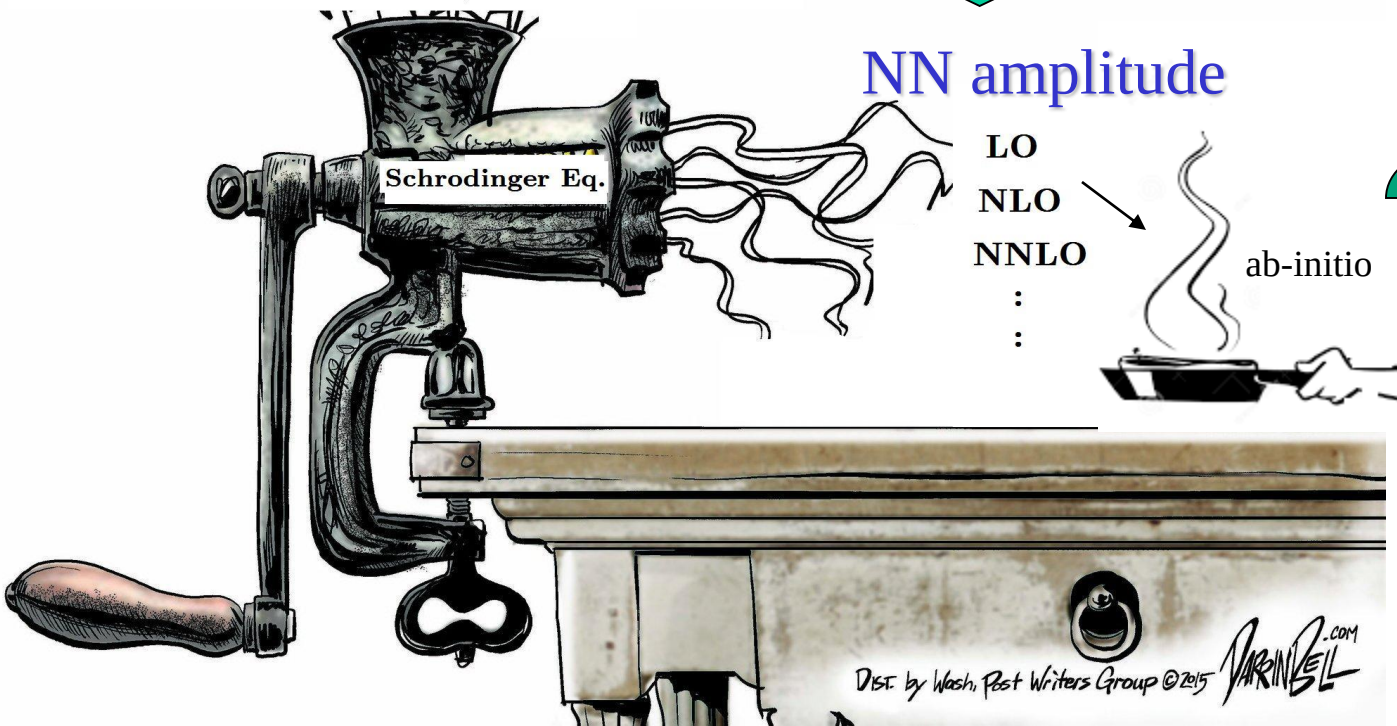
assumption

NN amplitude

LO
NLO
NNLO
:
:

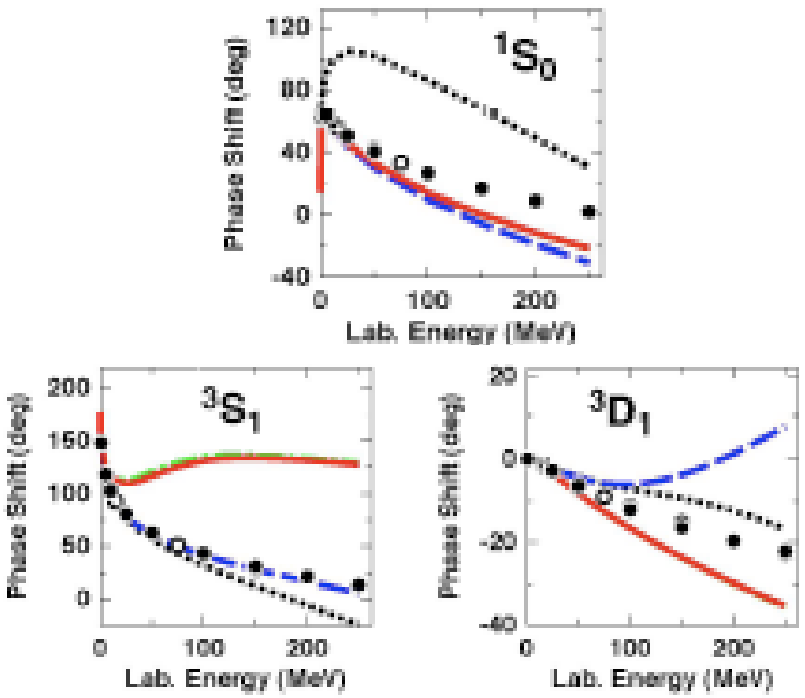
ab-initio

Properties of nuclei



Problems in RG

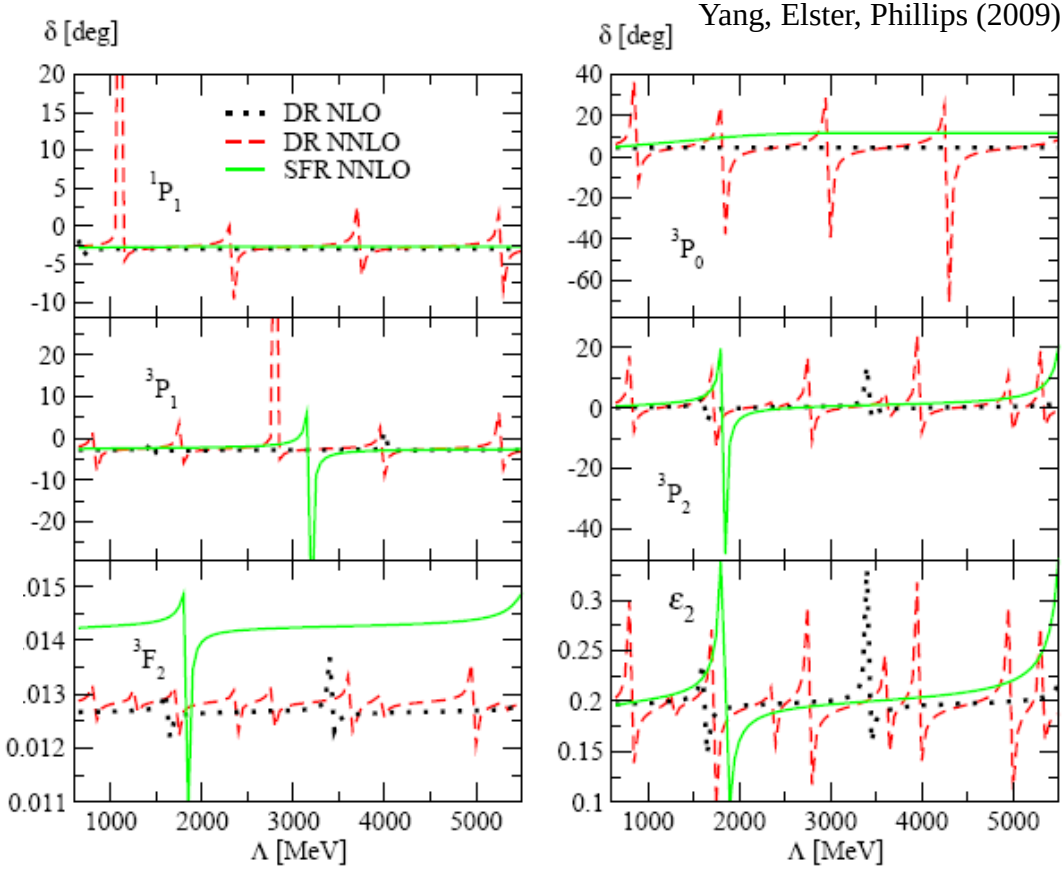
- Singular attractive potentials demand contact terms. (Nogga, Timmermans, van Kolck (2005))
- Beyond LO: RG problem at Λ>1 GeV (due to iteraion to all orders)



$N^3LO(Q^4)$

Ch. Zeoli R. Machleidt D. R. Entem (2012)

Yang, Elster, Phillips (2009)



Why is that a problem?

- Very complicated system, I know no details, only the symmetries of the system.
- Arrange the physics based on separation of scales.
- To get quantum corrections (loops) effect, need renormalization in most cases.
- EFT only makes sense only if renormalization group (RG) invariance is satisfied.

Physics cannot depend on cutoff

Mathematically:

Residual, ~O(1) if: 1. EFT works
2. $\Lambda \geq \overline{\Lambda}_{EFT}$

observables

order

$$\mathcal{O}(k, p_{typ}; \Lambda; \overline{\Lambda}_{EFT}) = \sum_{i}^{n} \left(\frac{k, p_{typ}}{\overline{\Lambda}_{EFT}} \right)^{i} \mathcal{O}_i(k, p_{typ}; \overline{\Lambda}_{EFT}) + \mathscr{C}_n(\Lambda; k, p_{typ}, \overline{\Lambda}_{EFT}) \left(\frac{k, p_{typ}}{\overline{\Lambda}_{EFT}} \right)^{n+1}$$

cutoff

Breakdown scale
(given by 1st meson not included)

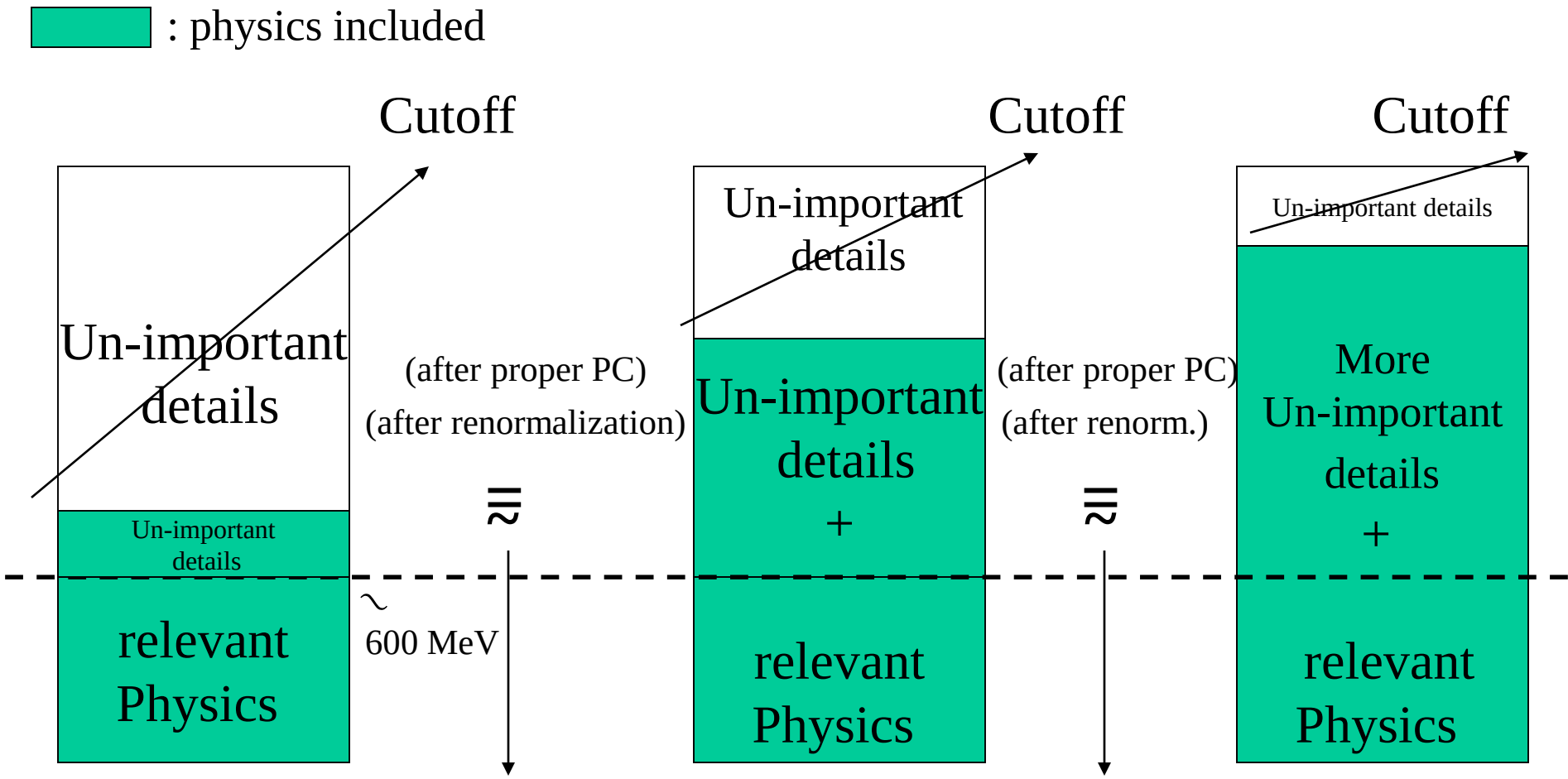
residual cutoff-dep.

No cutoff here! ***=> physics cannot depend on cutoff !***

H. W. Griesshammer, arXiv:1511.00490v3 [nucl-th].

Lepage plot: subtract at two Λ's to extract "n+1"

Renormalization group (RG)



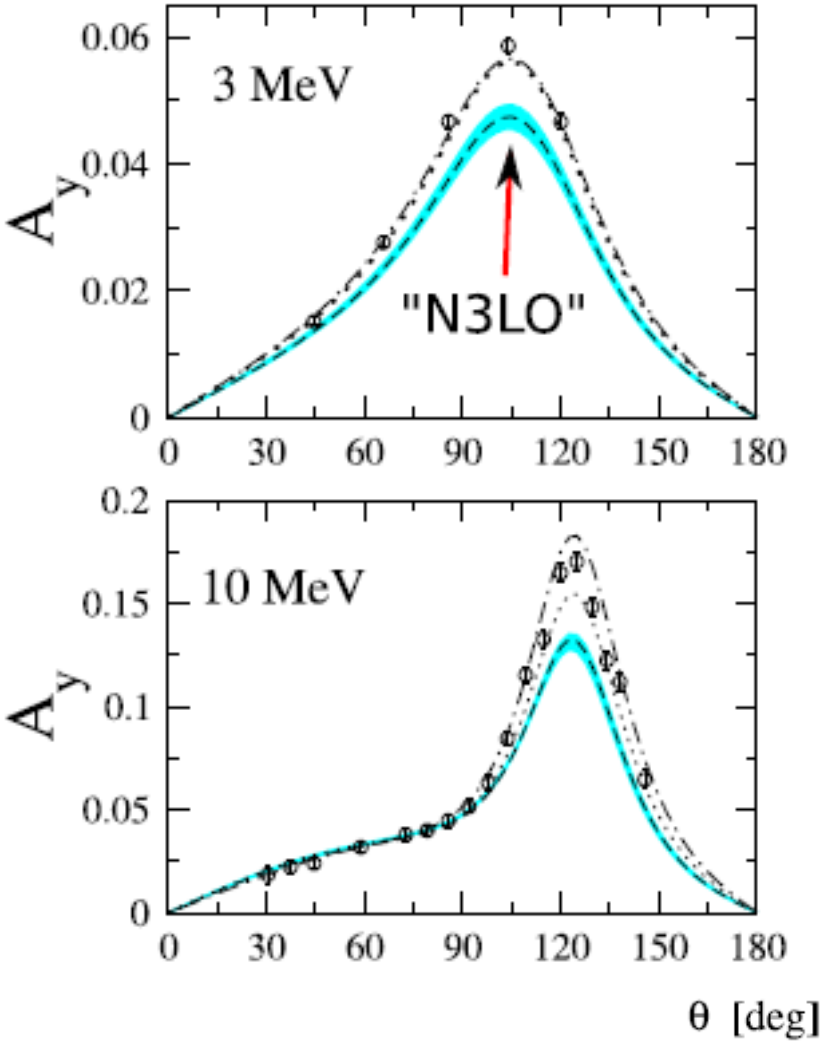
***Only source of error**: given by the high order terms.

If not so, → **the power counting isn't completely correct!**

(un-important are not really unimportant)

Some indications in the few-body sector

In the window: $500<\Lambda<875$ MeV



Known as the "A_y puzzle"

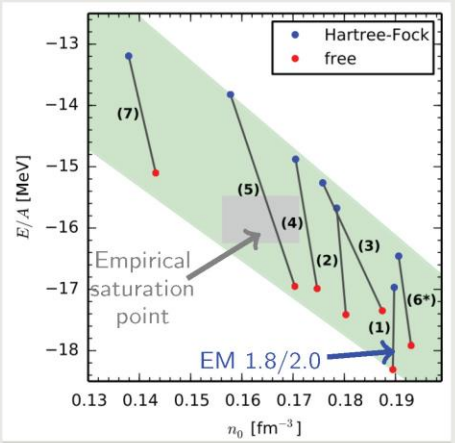
Entem et al, 2001

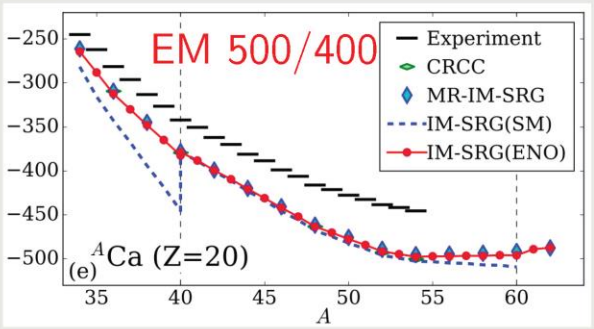
Some indications in nuclear structure

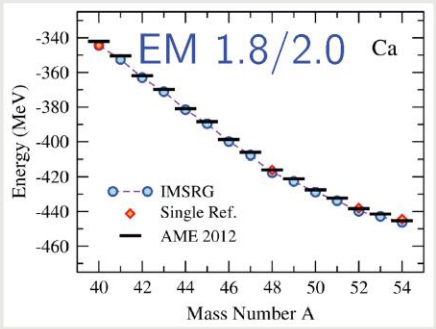
TRIUMF

One "magical" chiral (or chiral-inspired) interaction

	EM 500/400	EM 1.8/2.0
NN	N^{3}LO	same
	$\Lambda_{2N} = 500$ MeV	same
	non-local regulator	same
	fit to NN scattering, ^{2}H	same
	$\lambda_{SRG} = 1.88$ fm^{-1}	$\approx$ same
3N	N^{2}LO	same
	$\Lambda_{3N} = 400$ MeV	$\approx$ same
	local regulator	**non-local regulator**
	fit to ^{3}H BE, $t_{1/2}$	**fit to ^{3}H BE, ^{4}He r_{ch}**
	consistently SRG evolved	**no SRG for 3N**







- Neither interaction is fully consistent

  however. . .

- Saturation properties appear important for finite nuclei

Hebeler et al. PRC(R) (2011), Drischler et al. PRC (2016), Simonis et al. (in prep.)

Talk by R. S. Stroberg, ESNT workshop 2017

New power counting Long & Yang, (2010-2012)

Main idea

- In EFT, not all the terms in the Lagrangian must be included in the calculations (we have infinitely many terms, need to cut somewhere). Not all the terms need non-perturbatively treatment→ Only power counting decides.

Additional assumption

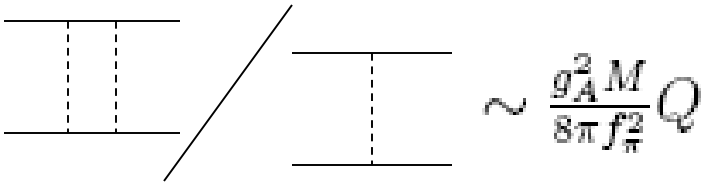
- Stop adding contact terms once RG is satisfied.

New power counting Long & Yang, (2010-2012)

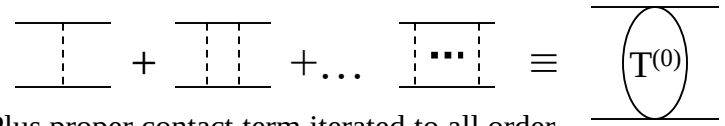
LO: Still iterate to all order (at least for most $l<2$).

Partial waves

Reason: van Kolck, Bedaque,… etc.



Thus, at LO:



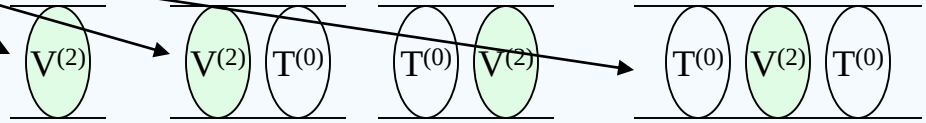
Plus proper contact term iterated to all order

Start at NLO, do perturbation. $(T = T^{(0)}+T^{(1)}+T^{(2)}+T^{(3)}+\ldots)$

If $V^{(1)}$ is absent:

$$T^{(2)} = V^{(2)} + 2V^{(2)}GT^{(0)} + T^{(0)}GV^{(2)}GT^{(0)}.$$

One insertion of $V^{(2)}$ in $T^{(0)}$



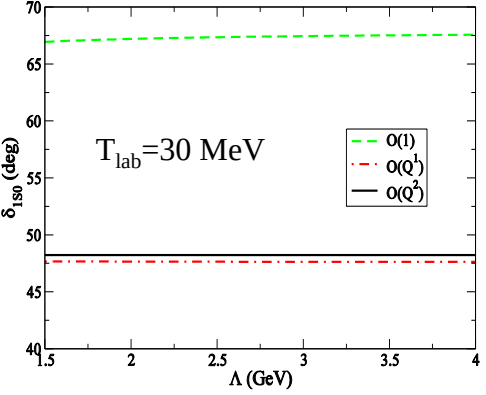
$$G \equiv \frac{2M_N}{\pi}\int_0^\Lambda \frac{p^2 dp}{p_0^2 - p^2 + i\varepsilon}$$

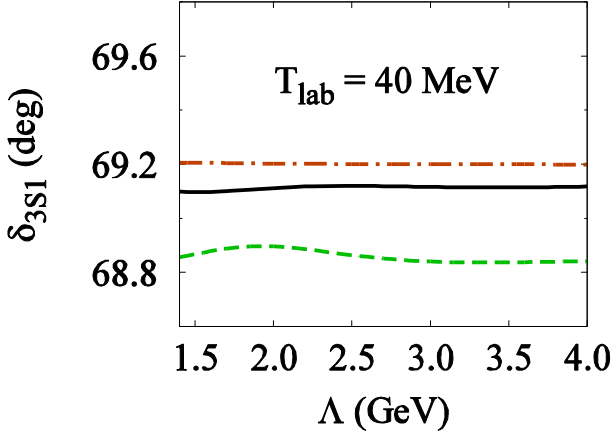
$$T^{(3)} = V^{(3)} + 2V^{(3)}GT^{(0)} + T^{(0)}GV^{(3)}GT^{(0)}.$$

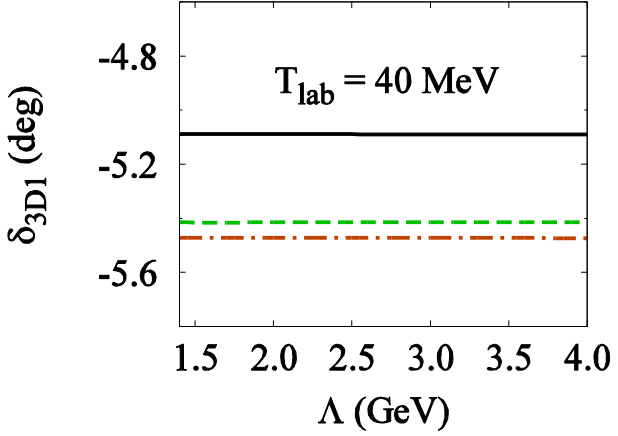
Results
(All RG-invariant)

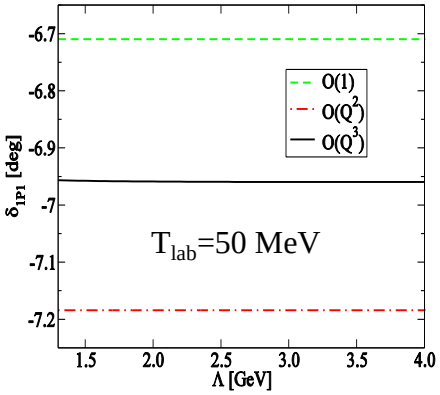
↓

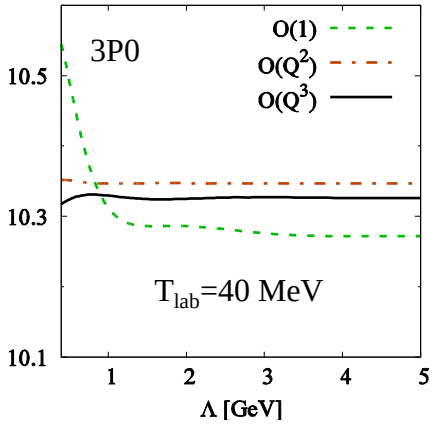
Satisfy the minimum requirement

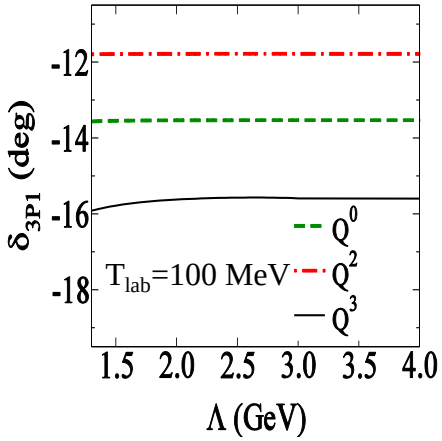

T_{lab}=30 MeV
O(1)
O(Q)
O(Q²)
δ_{1S0} (deg)
Λ (GeV)

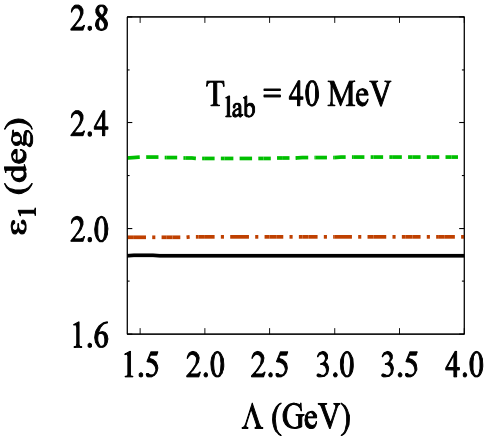

T_{lab} = 40 MeV
δ_{3S1} (deg)
Λ (GeV)

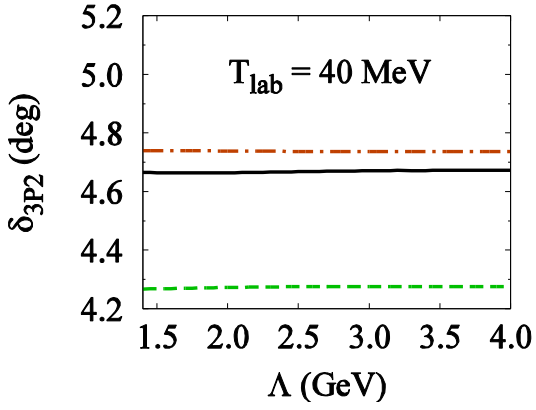

T_{lab} = 40 MeV
δ_{3D1} (deg)
Λ (GeV)

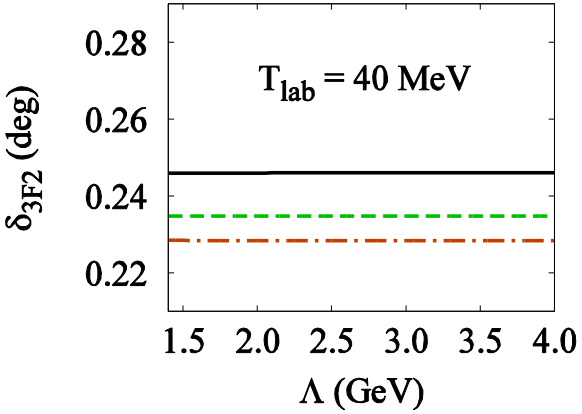

T_{lab}=50 MeV
O(1)
O(Q²)
O(Q³)
δ_{1P1} [deg]
Λ [GeV]

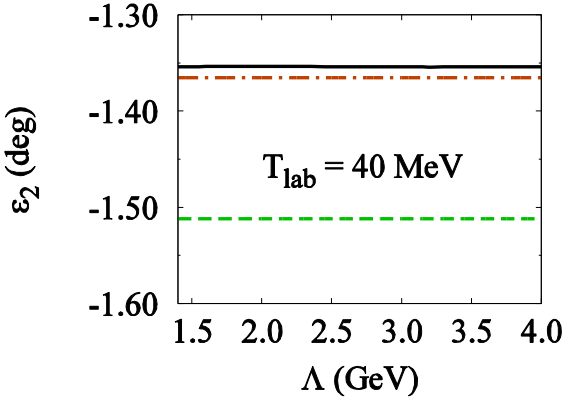

3P0
O(1)
O(Q²)
O(Q³)
T_{lab}=40 MeV
Λ [GeV]


T_{lab}=100 MeV
Q⁰
Q²
Q³
δ_{3P1} (deg)
Λ (GeV)


T_{lab} = 40 MeV
ε_1 (deg)
Λ (GeV)

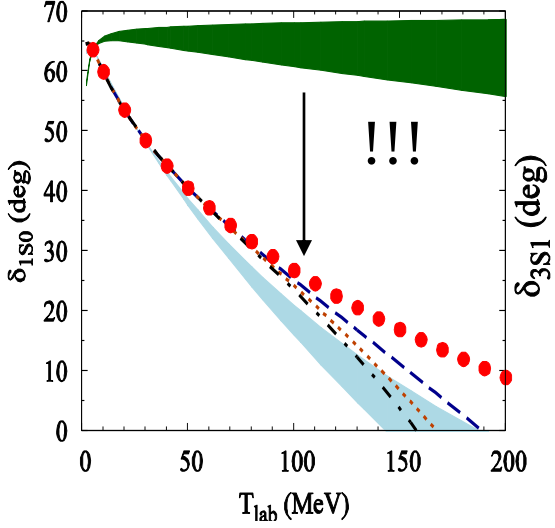

T_{lab} = 40 MeV
δ_{3P2} (deg)
Λ (GeV)

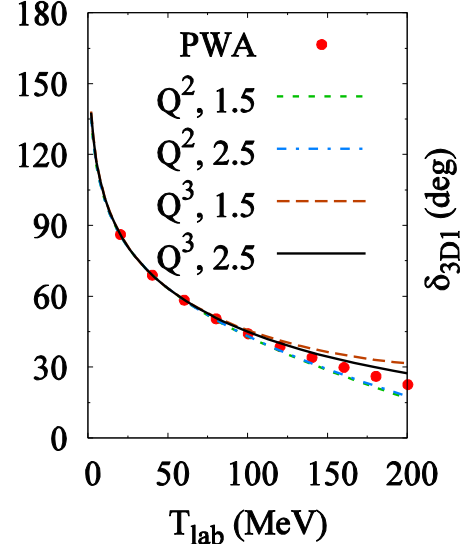

T_{lab} = 40 MeV
δ_{3F2} (deg)
Λ (GeV)

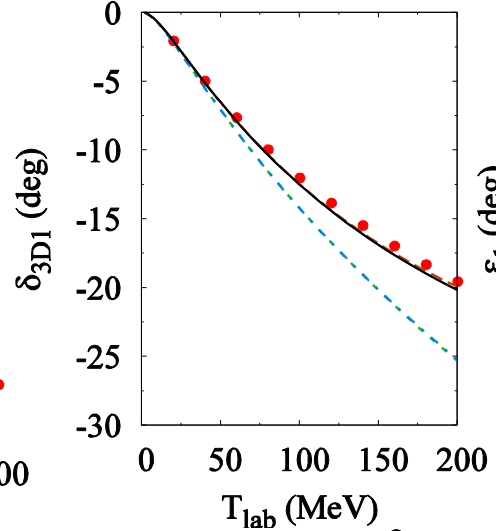

T_{lab} = 40 MeV
ε_2 (deg)
Λ (GeV)

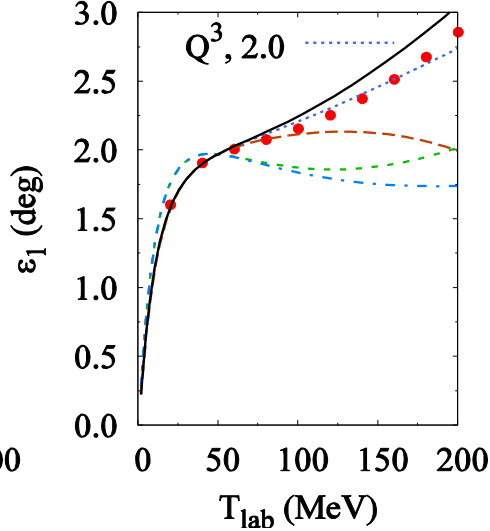
Quality of the fits

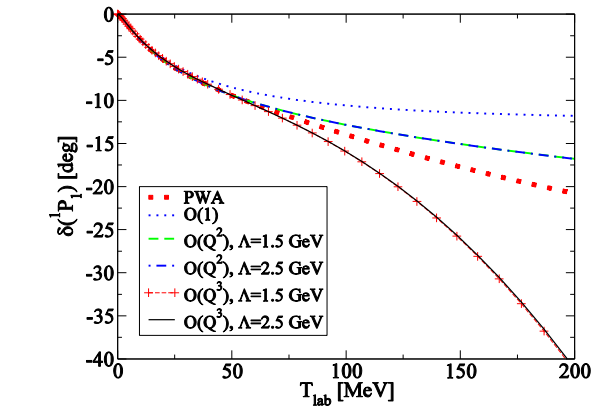
(comparable to WPC at the same order)

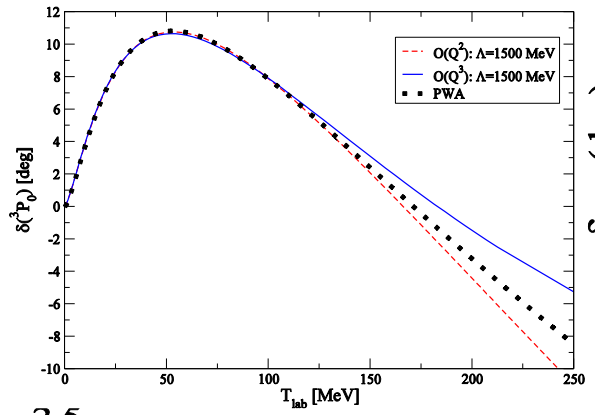

!!!
δ_{1S0} (deg)
T_{lab} (MeV)

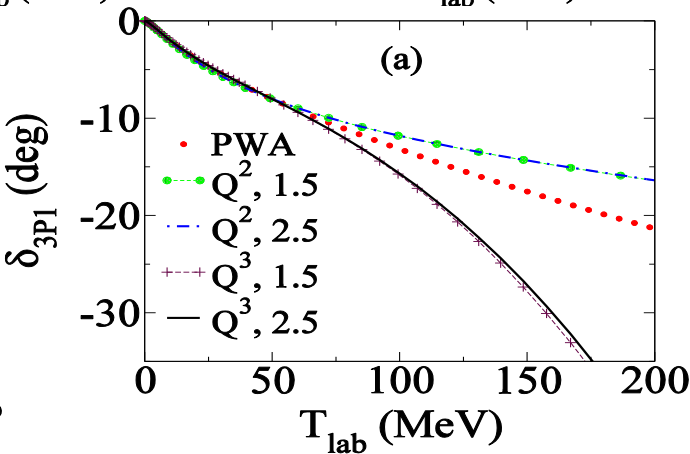

PWA
Q^2, 1.5
Q^2, 2.5
Q^3, 1.5
Q^3, 2.5
δ_{3S1} (deg)
T_{lab} (MeV)

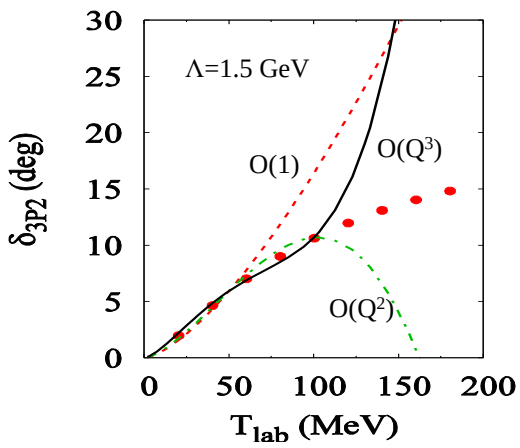

δ_{3D1} (deg)
T_{lab} (MeV)

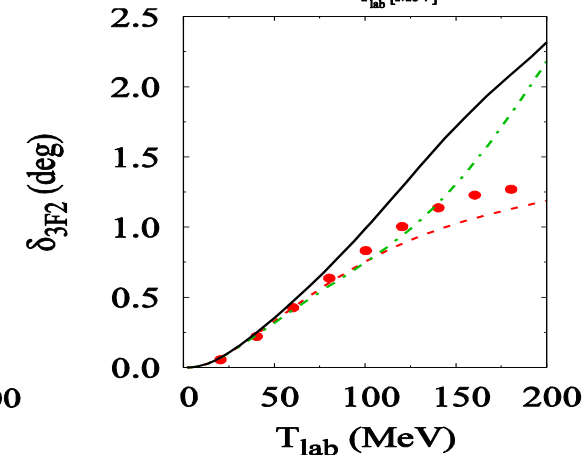

Q^3, 2.0
ε_1 (deg)
T_{lab} (MeV)

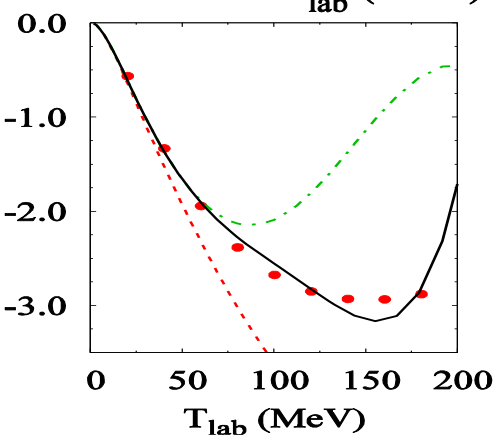

PWA
O(1)
O(Q^2), Λ=1.5 GeV
O(Q^2), Λ=2.5 GeV
O(Q^3), Λ=1.5 GeV
O(Q^3), Λ=2.5 GeV
$\delta(^1P_1)$ [deg]
T_{lab} [MeV]


O(Q^2): Λ=1500 MeV
O(Q^3): Λ=1500 MeV
PWA
$\delta(^3P_0)$ [deg]
T_{lab} [MeV]


(a)
PWA
Q^2, 1.5
Q^2, 2.5
Q^3, 1.5
Q^3, 2.5
δ_{3P1} (deg)
T_{lab} (MeV)

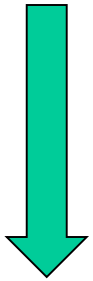

Λ=1.5 GeV
O(1)
O(Q^3)
O(Q^2)
δ_{3P2} (deg)
T_{lab} (MeV)


δ_{3F2} (deg)
T_{lab} (MeV)


ε_2 (deg)
T_{lab} (MeV)

Further improvement in 1S0

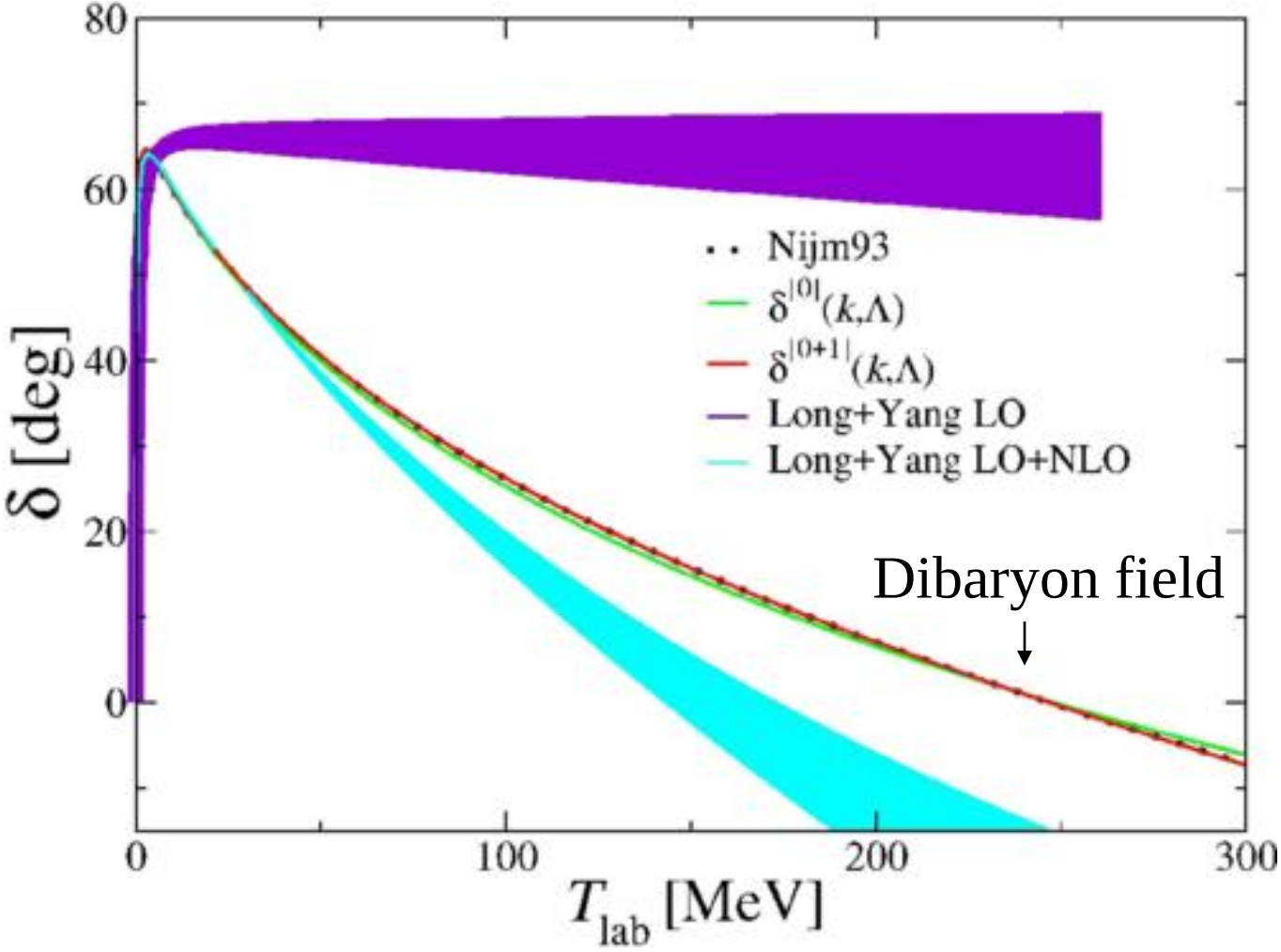
- At LO, although RG-invariant, the converged phase shifts are far from data.
- Worrisome big change (>100%) from LO to NLO.



After many (historical) struggles

Solution: Adopt dibaryon fields !

1.5 di-baryon field+OPE



Phys.Rev. C97 (2018) no.2, 024001

To be continued… in nuclear structure calculations

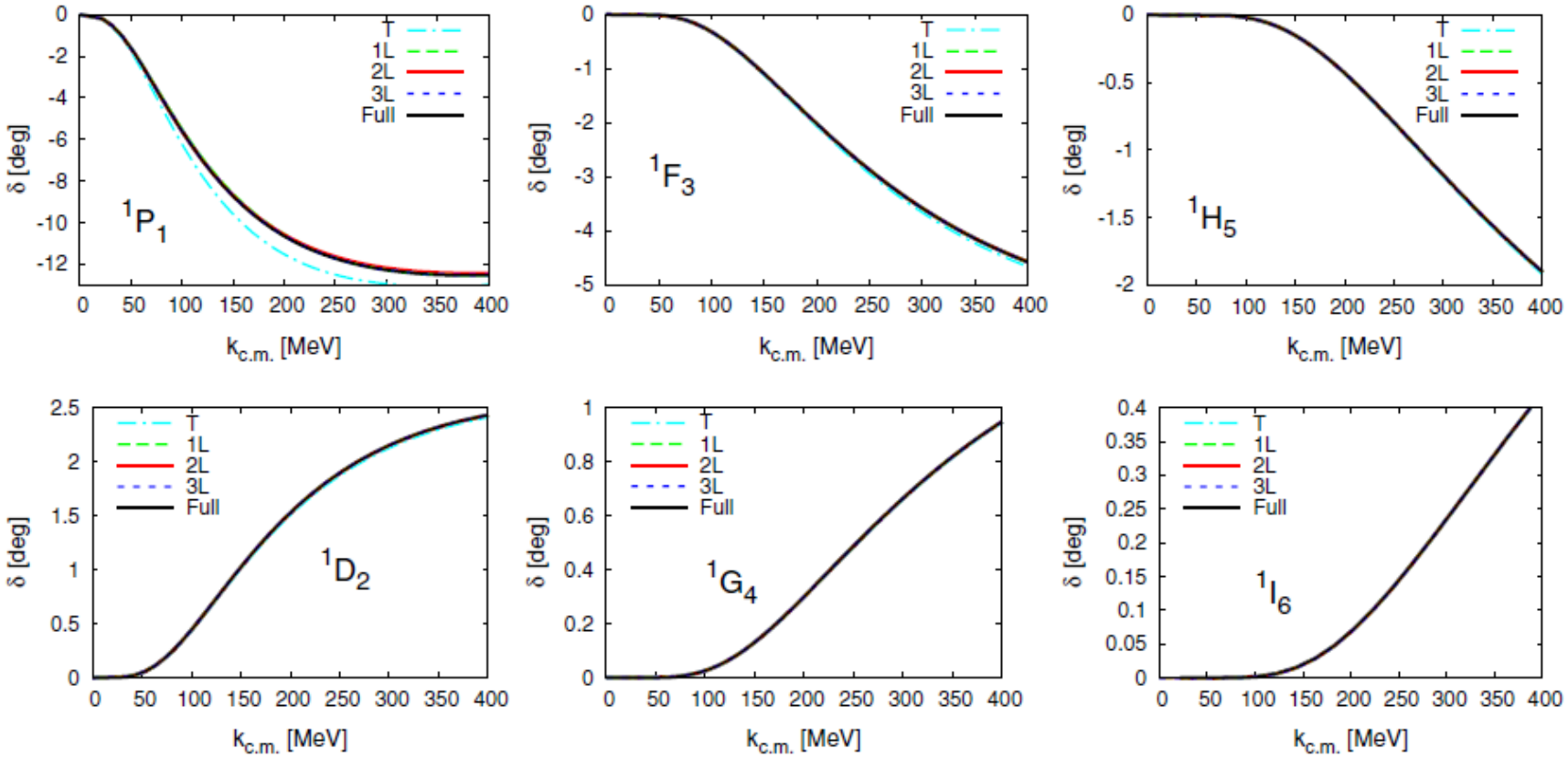
(In Chamlers: with A. Ekström, C. Forssén, G. Hagen)

Thank you!

Demotion due to higher *l*

M. Valderrama, et al, Phys.Rev. C95 (2017) no.5, 054001

First, check and confirmed that for spin singlet higher partial-waves, OPE can be treated perturbative.



Demotion due to higher *l*

M. Valderrama, et al, Phys.Rev. C95 (2017) no.5, 054001

Next, $\langle p,l|V|p',l\rangle = \frac{4\pi}{M_N}\frac{1}{\Lambda_{NN}} f_l\left(\frac{p}{m_\pi},\frac{p'}{m_\pi}\right)$

(Λ_{NN} ~300 MeV)

Make the potential attractive, and change this to $\Lambda^*_{NN}(l)$ until first bound state E_b~0 appears.

⇩

This indicates "how far" the perturbative series is from its own breakdown.

⇩

Compare $\Lambda^*_{NN}(l)$ at different *l* to 1s0 tells the relative "demotion" to S-wave

${}^{s}L_{J}$	$\Lambda_{NN}/\Lambda^{*}_{NN}(l)$	$\mathrm{N^{\nu}LO}$
${}^{1}P_{1}$	−6.40	$\mathrm{N^{1.0–1.7}LO}$
${}^{1}F_{3}$	−27.9	$\mathrm{N^{1.7–3.0}LO}$
${}^{1}H_{5}$	−64.6	$\mathrm{N^{2.1–3.8}LO}$
${}^{1}J_{7}$	−116.4	$\mathrm{N^{2.4–4.3}LO}$
${}^{1}L_{9}$	−183.3	$\mathrm{N^{2.7–4.7}LO}$
${}^{1}N_{11}$	−265.4	$\mathrm{N^{2.9–5.1}LO}$
${}^{1}D_{2}$	45.8	$\mathrm{N^{2.0–3.5}LO}$
${}^{1}G_{4}$	133.1	$\mathrm{N^{2.5–4.5}LO}$
${}^{1}I_{6}$	265.9	$\mathrm{N^{2.9–5.1}LO}$
${}^{1}K_{8}$	444.0	$\mathrm{N^{3.1–5.5}LO}$
${}^{1}M_{10}$	667.4	$\mathrm{N^{3.3–5.9}LO}$

Back up slides

Some thoughts (Philosophical)

- God can set nature to any way he like.
- It can be that LO, NLO,..etc, not working (RG-fails), or each contains very large “un-natural” contribution, but they cancel out at N^nLO and thereafter. -> So you just need to have faith and carryout to that order.
- Or it could be that RG-failure only introduce small effect in the final amplitude if the cutoff is limited, so the wrong-ness of this PC is controllable or even order by order correctable.

We have done so much in one direction, why not try others.

RG-ok theory allows us to get full power of EFT.