Towards a relativistic formulation of baryon-baryon interactions in chiral perturbation theory

NN: arXiv:1611.08475
YN: arXiv:1612.08482

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Peter Ring, Technical University of Munich

SNP2017/2017.03.12

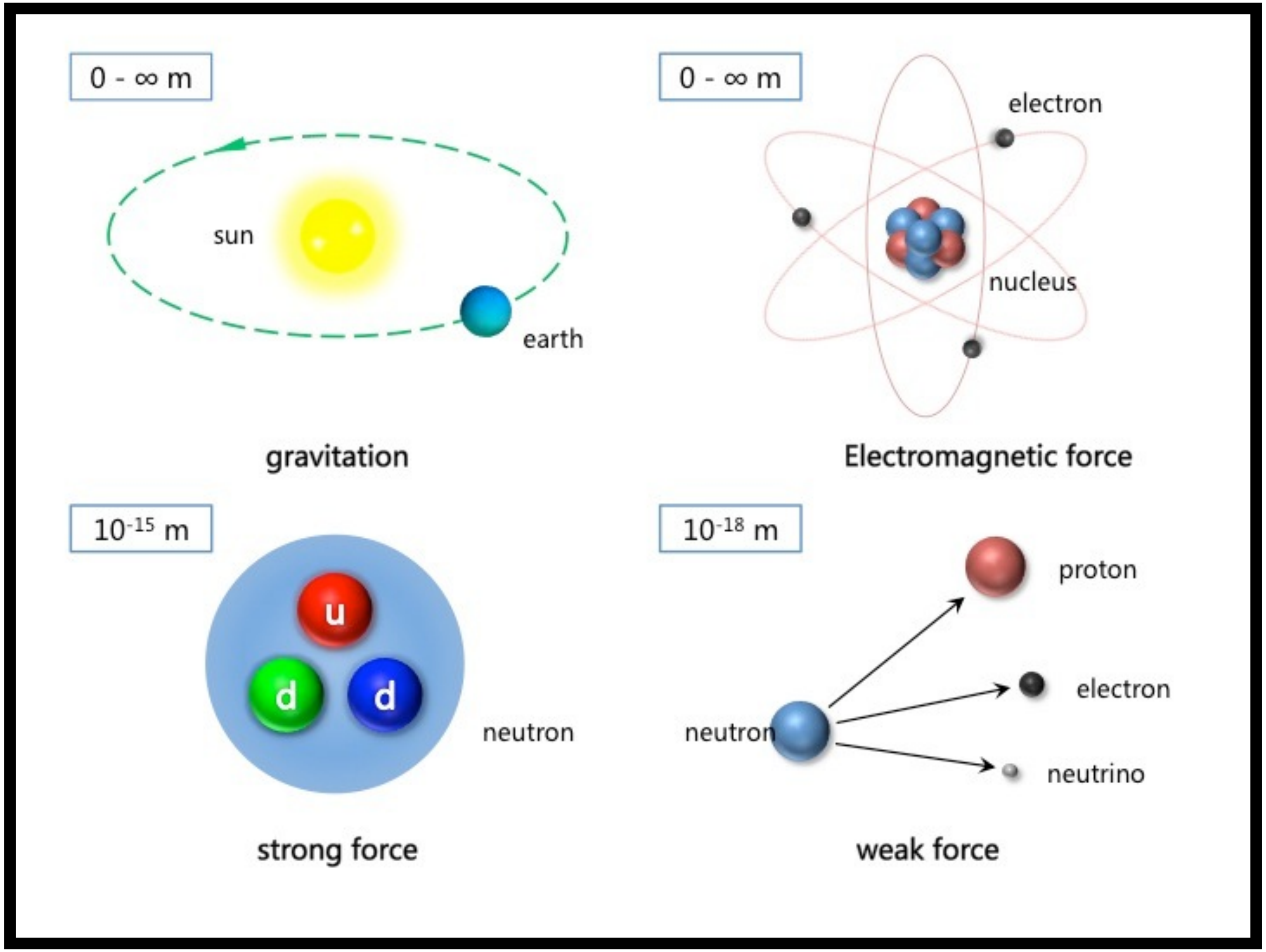
First step in a long journey

Outline

- **Introduction**
  - *Why nuclear force (baryon-baryon interactions);* ***Current status (of chiral forces)***
  - **Why relativistic? atomic/molecular; nuclear; one-baryon sector**
- **Our strategy and some leading order results**
  - **Nucleon-nucleon (NN)**
  - **Hyperon-nucleon (YN)**
- **Summary and outlook**

Motivation: why nuclear force

Four (established) forces in nature

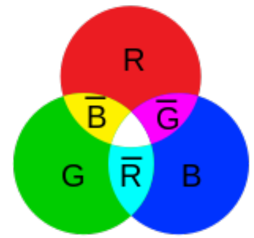


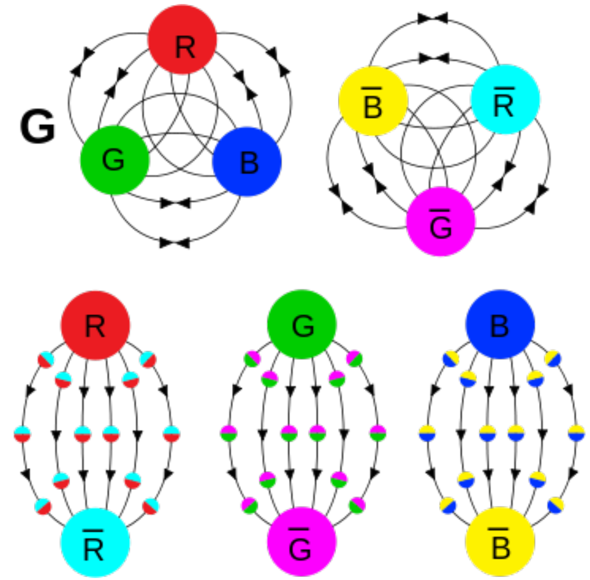
Evidence for a Protophobic Fifth Force from ^{8}Be Nuclear Transitions,1604.07411

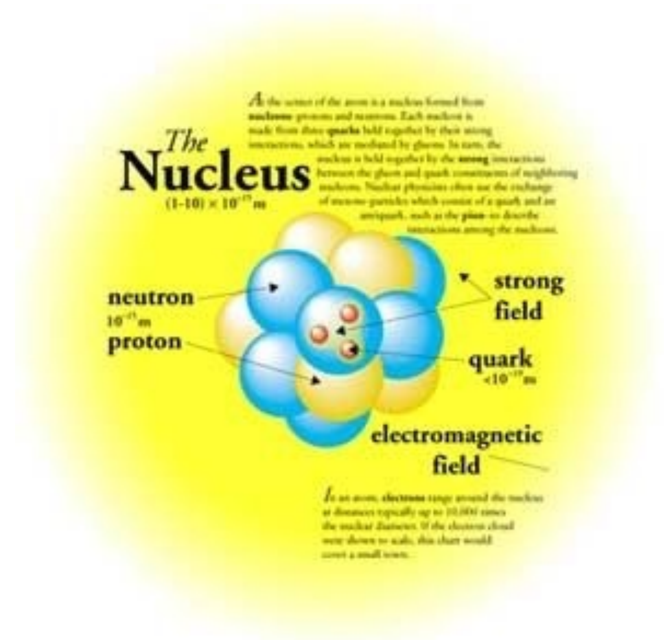
Strong force

- **Strong force:** bind quarks into hadrons
- **Nuclear force**—residual strong force: binds nucleons into nuclei
- **Underlying theory—QCD**

$$
\begin{aligned}
LQCD = &-\frac{1}{4}(\partial^{\mu}G_a^{\nu}-\partial^{\nu}G_a^{\mu})(\partial_{\mu}G_{\nu}^{a}-\partial_{\nu}G_{\mu}^{a})+\sum_f \bar{q}_f^{\alpha}(i\gamma^{\mu}\partial_{\mu}-m_f)q_f^{\alpha} \\
&+g_s G_a^{\mu}\sum_f \bar{q}_f^{\alpha}\gamma^{\mu}\left(\frac{\lambda^a}{2}\right)_{\alpha\beta} q_f^{\beta} \\
&-\frac{g_s}{2}f^{abc}(\partial^{\mu}G_a^{\nu}-\partial^{\nu}G_a^{\mu})G_{\mu}^{b}G_{\nu}^{c}-\frac{g_s^2}{4}f^{abc}f_{ade}G_b^{\mu}G_c^{\nu}G_{\mu}^{d}G_{\nu}^{e}
\end{aligned}
$$

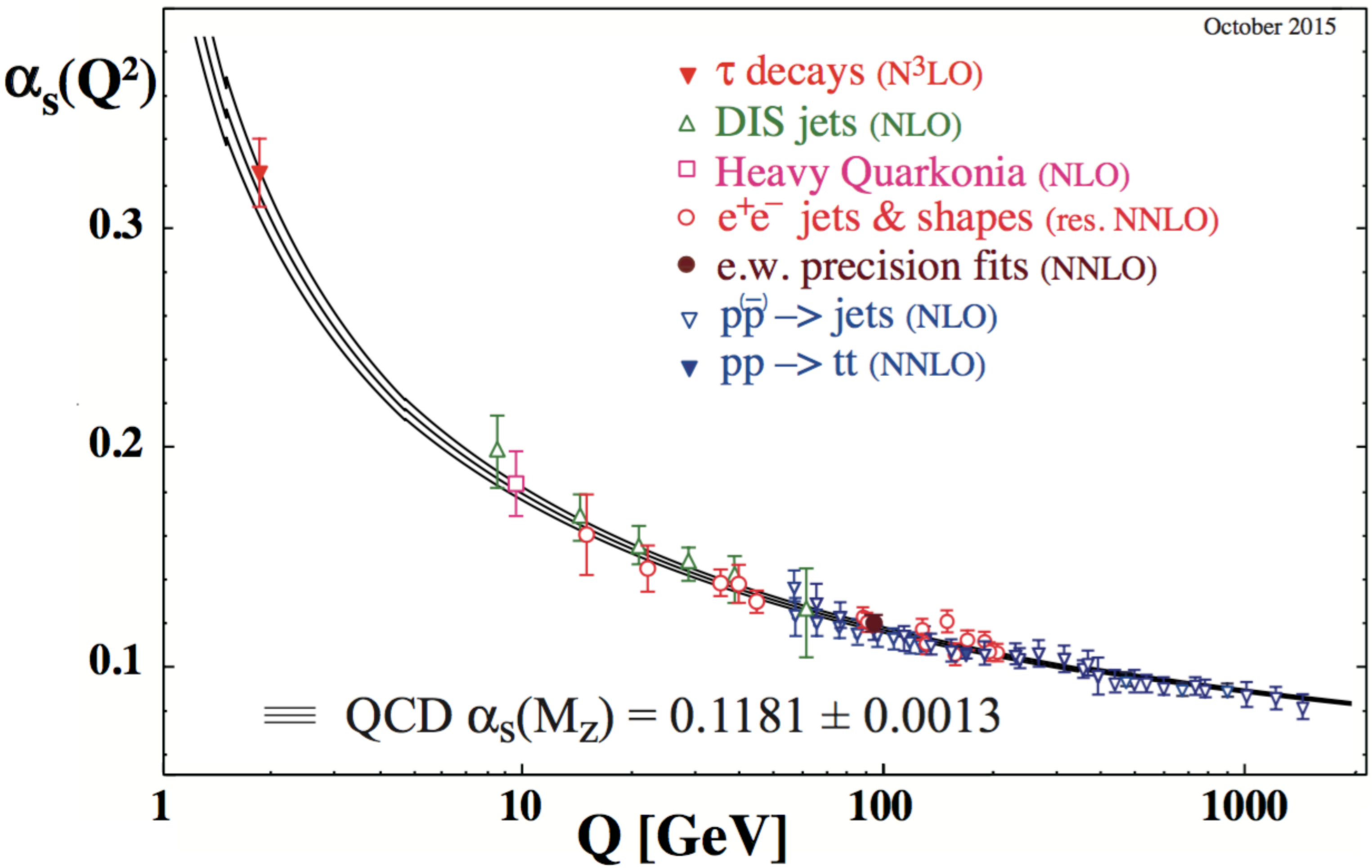






2 quark masses and 1 universal coupling

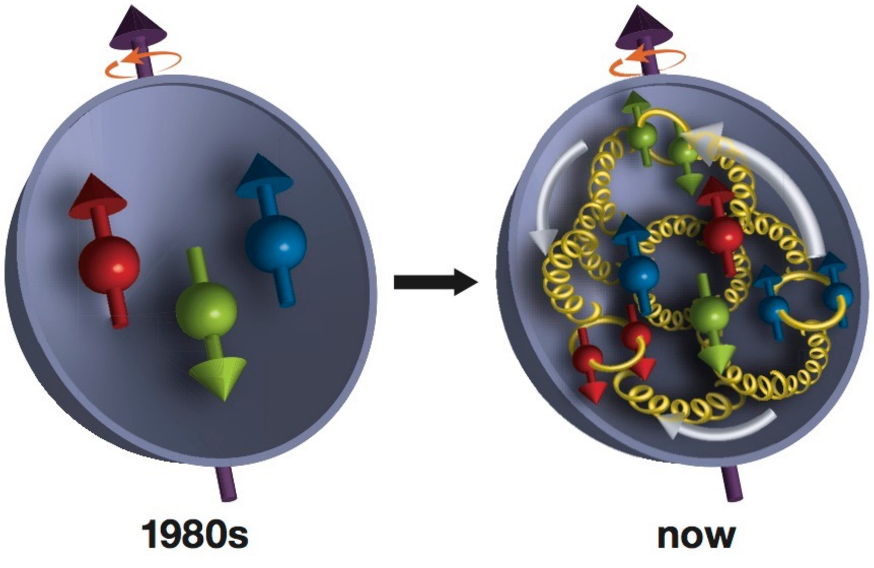
QCD：Asymptotic freedom



PDG2015

QCD： color confinement

- **Free quarks do not exist (color confinement), experimentally only hadrons are observed**
- **Mismatch of degrees of freedom— hadronization**



Decomposition of the proton spin

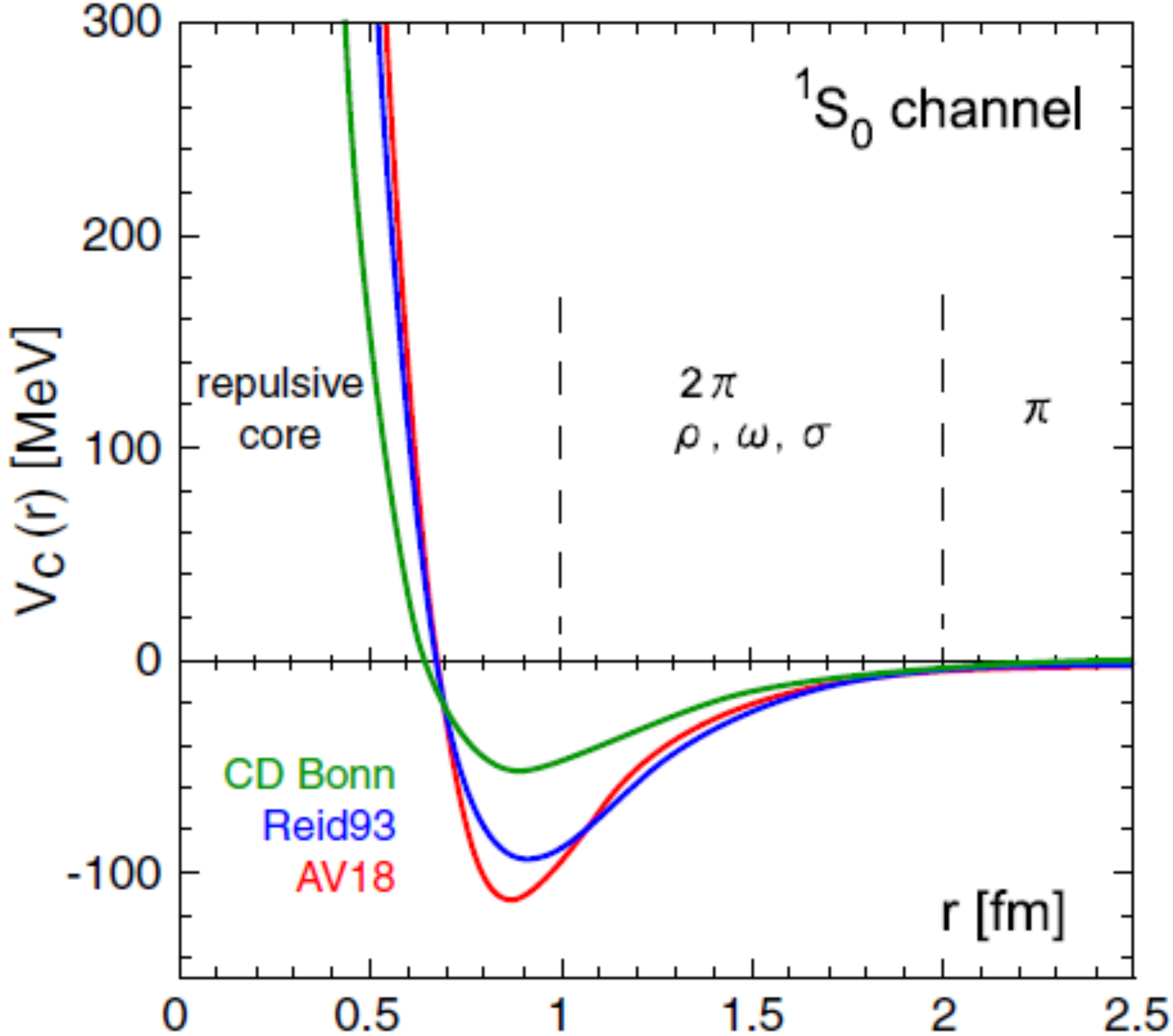
Why construct nuclear forces?

- **Nuclear force: derivative force or residual force**
- **In this sense, similar to intermolecular force, but because of confinement and asymptotic freedom of QCD, much richer and harder**

Fan Wang, Guang-han Wu, Li-jian Teng, J.Terrance Goldman Phys.Rev.Lett. 69 (1992) 2901-2904

- **Constructing a nuclear force is a long-standing and interesting subject in nuclear physics; the basis of all microscopic (ab initio) nuclear structure and reaction theories**

“High Precision” Nuclear Force



“On the interaction of elementary particles,” PTP17,48

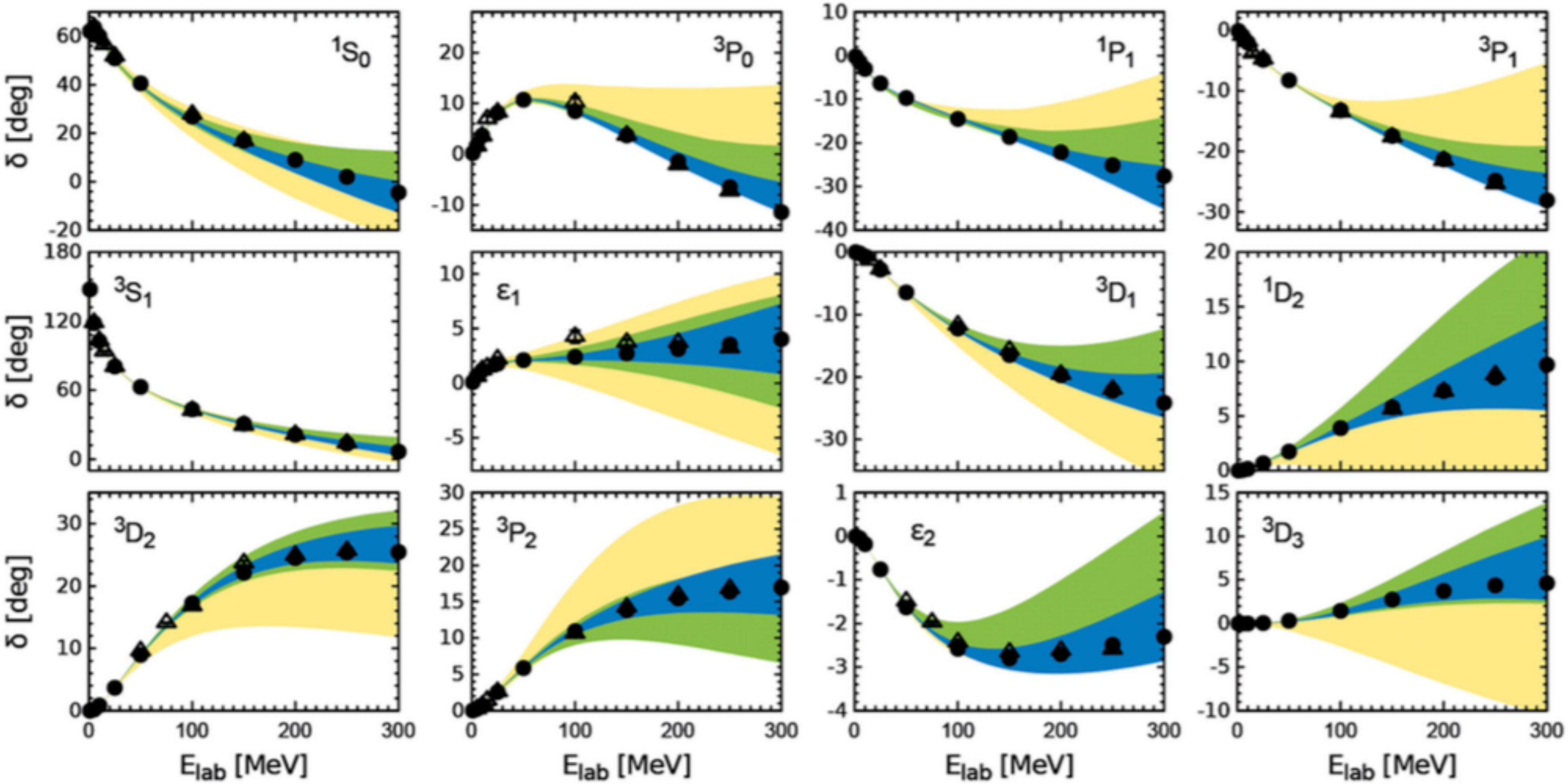
Major milestones for NN potential development ChPT

- **1991/92: Weinberg, NN potential from ChPT**
- **1994/96: Bira v. Kolck and co-workers, first ChPT based NN potential at N2LO using cutoff regularization (r-space)**
- **1994-1997:**
  - **Robilotta and co-workers, 2-pi at N2LO**
  - **1997: Kaiser et al., 2-pi at N2LO using HBChPT and DR**
- **2000: Epelbaum et al. ("Bochum-Juelich" group), NN potential in momentum space at N2LO (HBChPT, DR)**

High Precision Nuclear Force

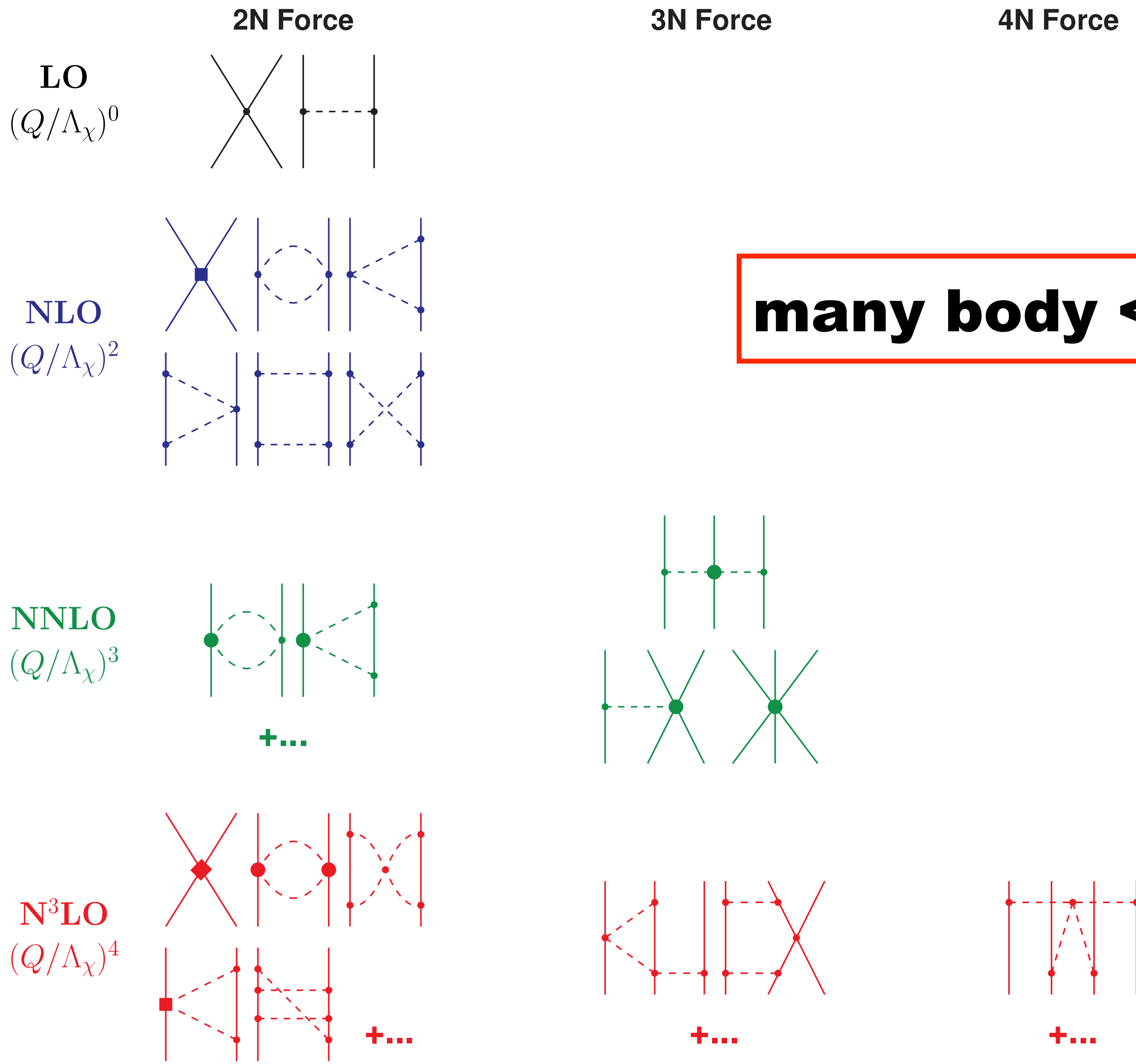
- **2003:**
  - **Robilotta and co-workers 2-pi at N3LO in RBChPT**
  - **Entem & Machleidt ("Idaho" group), first NN potential at N3LO (HBChPT, DR)**
- **2005: Epelbaum et al. ("Bochum-Juelich" group), NN potential at N3LO (HBChPT, SFR)**
- **2015: Epelbaum et al., Entem, et al., NN potential at N4LO**

Estimate of theoretical uncertainties



- **E. Epelbaum, H. Krebs, and U.-G. Meissner, Eur. Phys. J. A (2015)51**

Hierarchy of Bare Nuclear Force in ChEFT



many body < few body

- **E. Epelbaum, H.-W. Hammer, Ulf-G. Meissner, Reviews of Modern Physics 81(2009)1773**
- **R. Machleidt and D. R. Entem, Physics Reports 503(2011)1**

Nonrelativistic NF from heavy baryon (HB) ChEFT

- **NN interaction**
  - up to NLO U. van Kolck et al., PRL, PRC1992-94; N. Kaiser, NPA1997
  - up to NNLO E. Epelbaum, et al.,NPA2000; U. van Kolck et al.,PRC1994
  - up to N^3LO R. Machleidt et al., PRC2003; E. Epelbaum et al., NPA2005
  - up to N^4LO E. Epelbaum et al., PRL2015, D.R. Entem, et al., PRC2015
  - dominant N^5LO terms D.R. Entem, et al., PRC2015
- **3N interaction**
  - up to NNLO U. van Kolck, PRC1994
  - up to N^3LO S. Ishikwas, et al, PRC2007; V. Bernard et al, PRC2007;
  - up to N^4LO H. Krebs, et al., PRC2012-13
- **4N interaction**
  - up to N^3LO E. Epelbaum, PLB 2006, EPJA 2007

Number of parameters in Modern Nuclear Forces

					ChEFT [5]				
	PWA93 [1]	Reid93 [2]	AV18 [3]	CD-Bonn [4]	LO	NLO	NNLO	N3LO	N4LO
No. of LECs	35	50	40	38	2	9	9	24	24
χ^2/ datum	1.07	1.03	1.09	1.02	480	63	21	0.7	0.3

caution about definition of χ^2

[1] V.G.J. Stocks et al., PRC48, 792(1993)—Inspire cited 637 times

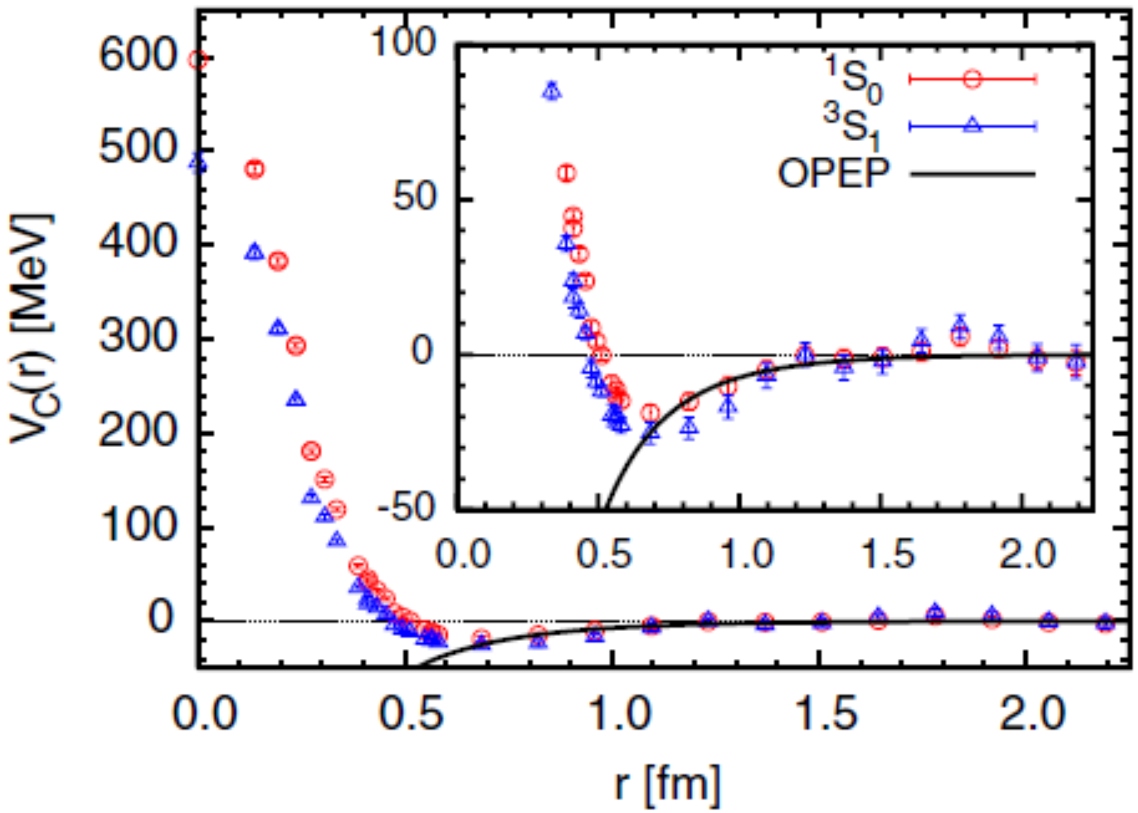
[2] V.G.J. Stocks et al., PRC49, 2950(1994)—Inspire cited 1054 times

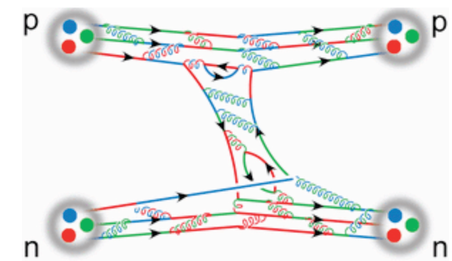
[3] Robert B. Wiringa et al, PRC51, 38(1995)—Inspire cited 1975 times

[4] R. Machleidt, PRC63,024001(2001)—Inspire cited 1050 times

[5] PRL 115,122301(2015)—Inspire cited 58

Nuclear Force from Quark-Gluon dofs





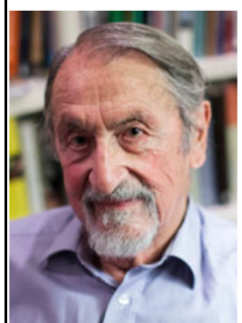
- **First qualitative nuclear force from first principles**
- **m_π=461 MeV**
- **Quenched**

N. Ishii et al., PRL99,022001(2007)

H. Nemura	Tsukuba Univ.	Lambda–N and Sigma–N interactions from 2+1 lattice QCD
K. Sasaki	YITP	QCD simulations on the S = −2 baryon–baryon interaction

The ultimate aim:
nuclear physics as a precision science

The Nobel Prize in Chemistry 2013



© Harvard University
Martin Karplus

Photo: © S. Fisch
Michael Levitt

Photo: Wikimedia Commons
Arieh Warshel

The Nobel Prize in Chemistry 2013 was awarded jointly to Martin Karplus, Michael Levitt and Arieh Warshel *"for the development of multiscale models for complex chemical systems"*.

for the development of multiscale models for complex chemical systems

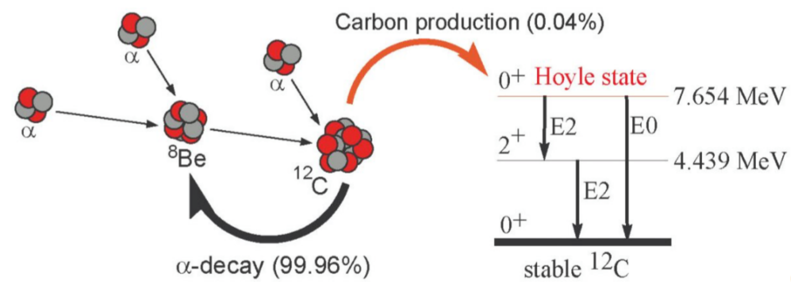
Nuclear force+advanced numerical methods

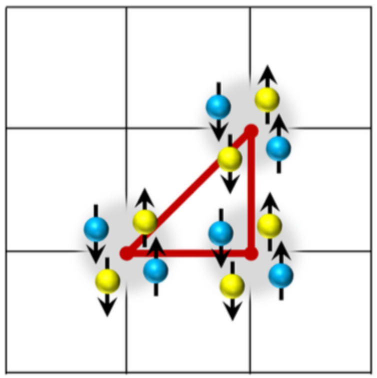
=

precision nuclear physics

Two recent examples

Hoyle state of Carbon





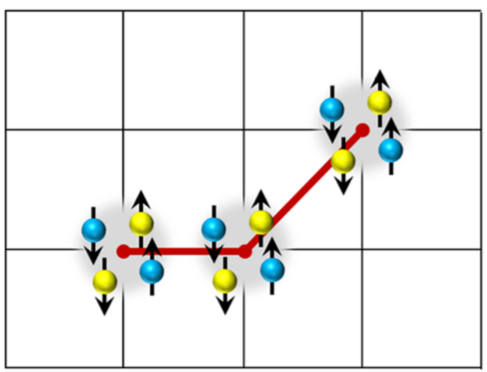


TABLE II. Lattice and experimental results for the energies of the low-lying even-parity states of ^{12}C, in units of MeV.

	0_1^+	$2_1^+(E^+)$	0_2^+	$2_2^+(E^+)$
LO	−96(2)	−94(2)	−89(2)	−88(2)
NLO	−77(3)	−74(3)	−72(3)	−70(3)
NNLO	−92(3)	−89(3)	−85(3)	−83(3)
Expt.	−92.16	−87.72	−84.51	−82.6(1) [8,10]
				−81.1(3) [9]
				−82.32(6) [11]

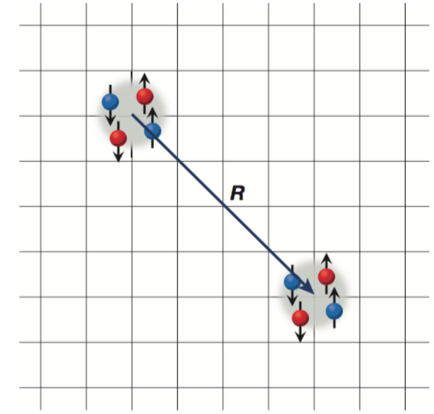
PRL 109, 252501 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

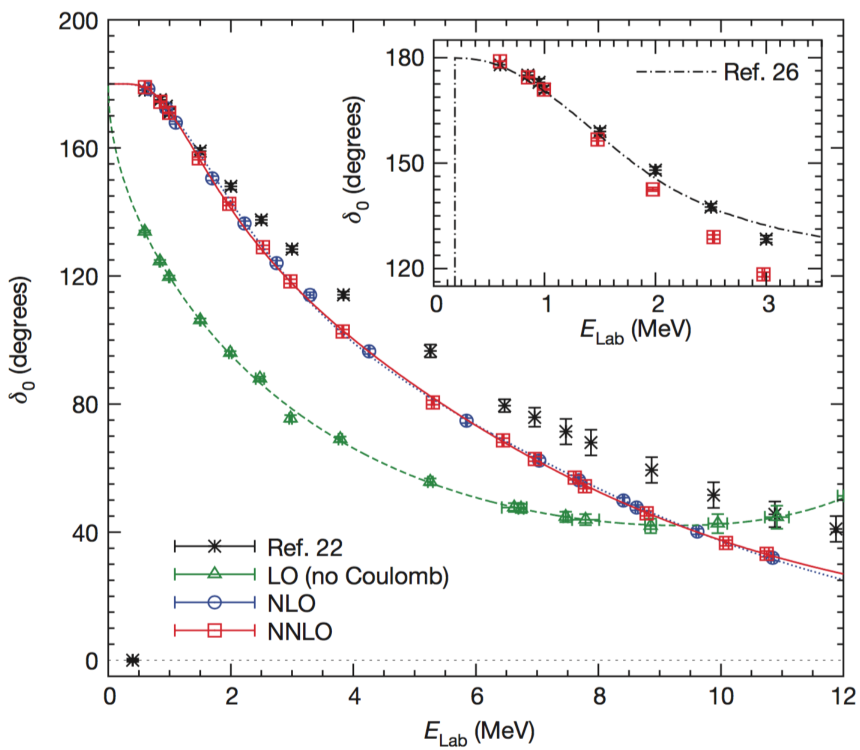
Structure and Rotations of the Hoyle State

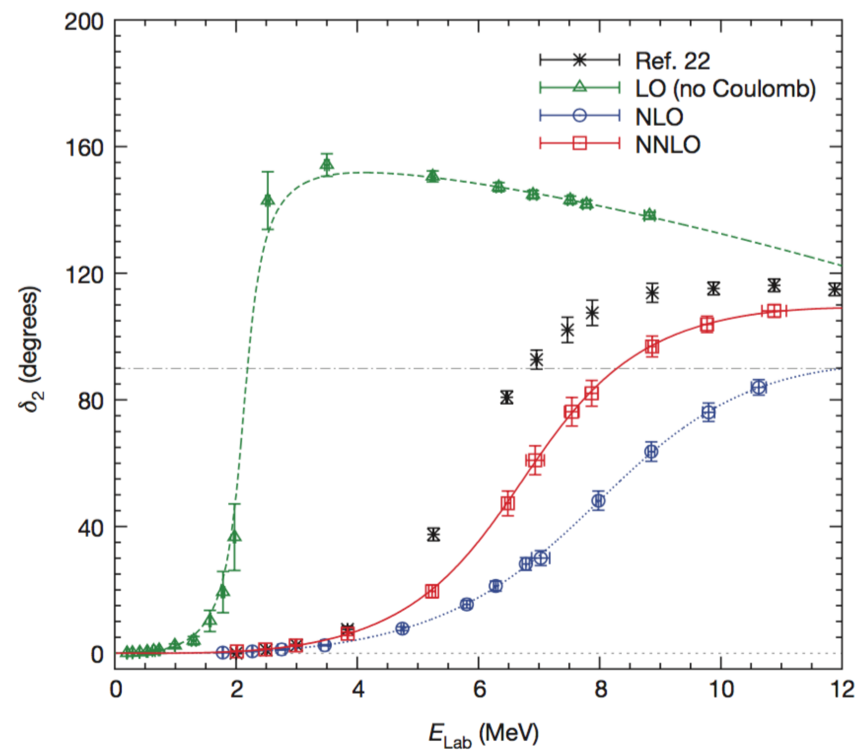
Evgeny Epelbaum,[1] Hermann Krebs,[1] Timo A. Lähde,[2] Dean Lee,[4] and Ulf-G. Meißner[5,2,3]

Two recent examples

alpha-alpha scattering







LETTER

doi:10.1038/nature16067

Ab initio alpha–alpha scattering

Serdar Elhatisari[1], Dean Lee[2], Gautam Rupak[3], Evgeny Epelbaum[4], Hermann Krebs[4], Timo A. Lähde[5], Thomas Luu[1,5] & Ulf-G. Meißner[1,5,6]

Nature 16067

Limitations of Current ChPT NN forces

- **Not “renormalization group invariant”**
  - Sensitive to the UV cutoff, not (non-perturbatively) renormalizable
  - Diverse opinion on this issue (Bira Van Kolck et al.)
- **Based on HBChPT**
  - Slow convergence as in the one-baryon sector?

    D. R. Entem, N. Kaiser, R. Machleidt, and Y. Nosyk, Phys. Rev. C92, 064001 (2015).

  - Cannot be used directly in covariant calculations.
- **A relativistic nuclear force based on the EOMS BChPT more relativistic nuclear studies?**

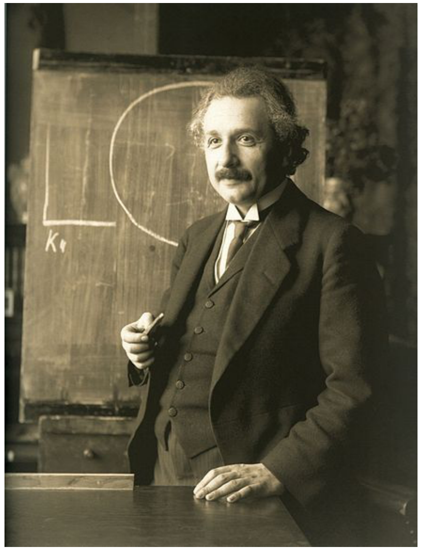
Motivation: why relativistic

Importance of Relativity not so much recognized

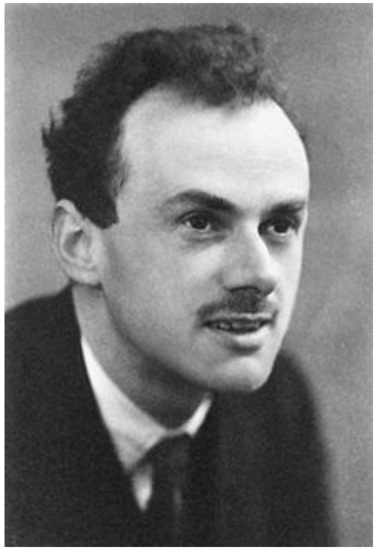
- **Two pillars of modern physics:**
  - ✓ **Quantum mechanics**
  - ✓ **Special relativity**

S.L.Glashow, 1988, Interactions, Wamer Books, New York

Modern elementary-particle physics is founded upon the two pillars of quantum mechanics and relativity. ……Thus it is that a satisfactory description of the atom can be obtained without Einstein's revolutionary theory.



Relativistic effects in a nutshell



- **Kinematical effects**
  - **Length contraction, time dilation, ...**

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

- **Dynamical effects**

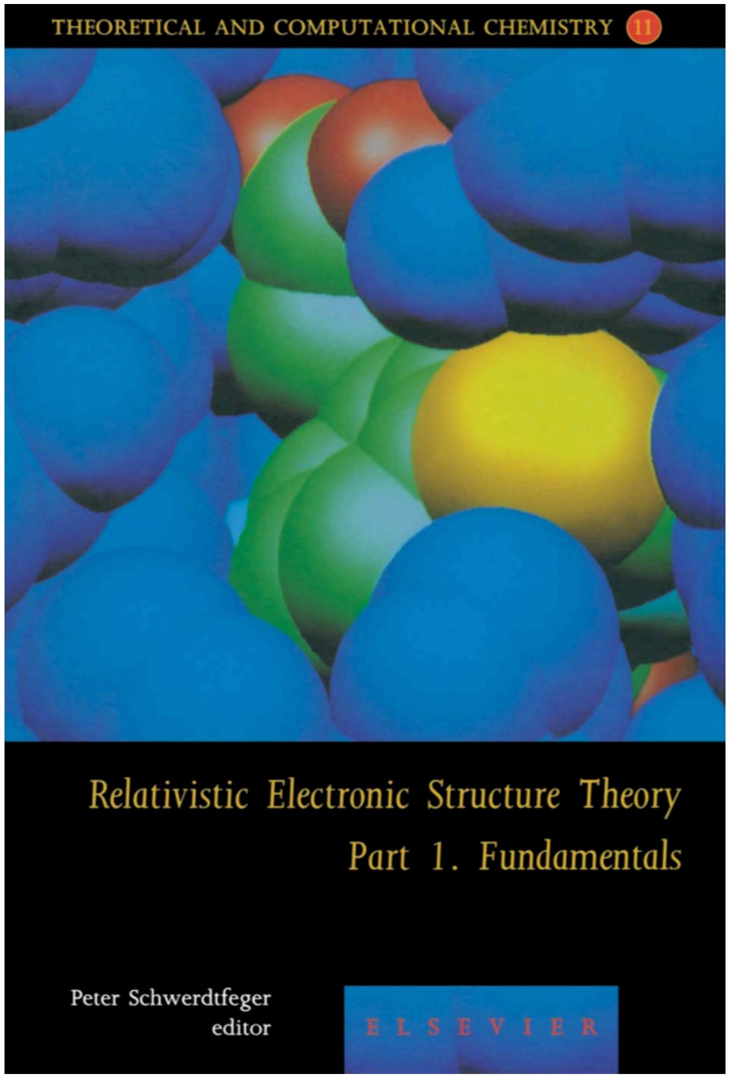
$$\boxed{\left[i\gamma^{\mu}\partial_{\mu} - m\right]\psi = 0}$$

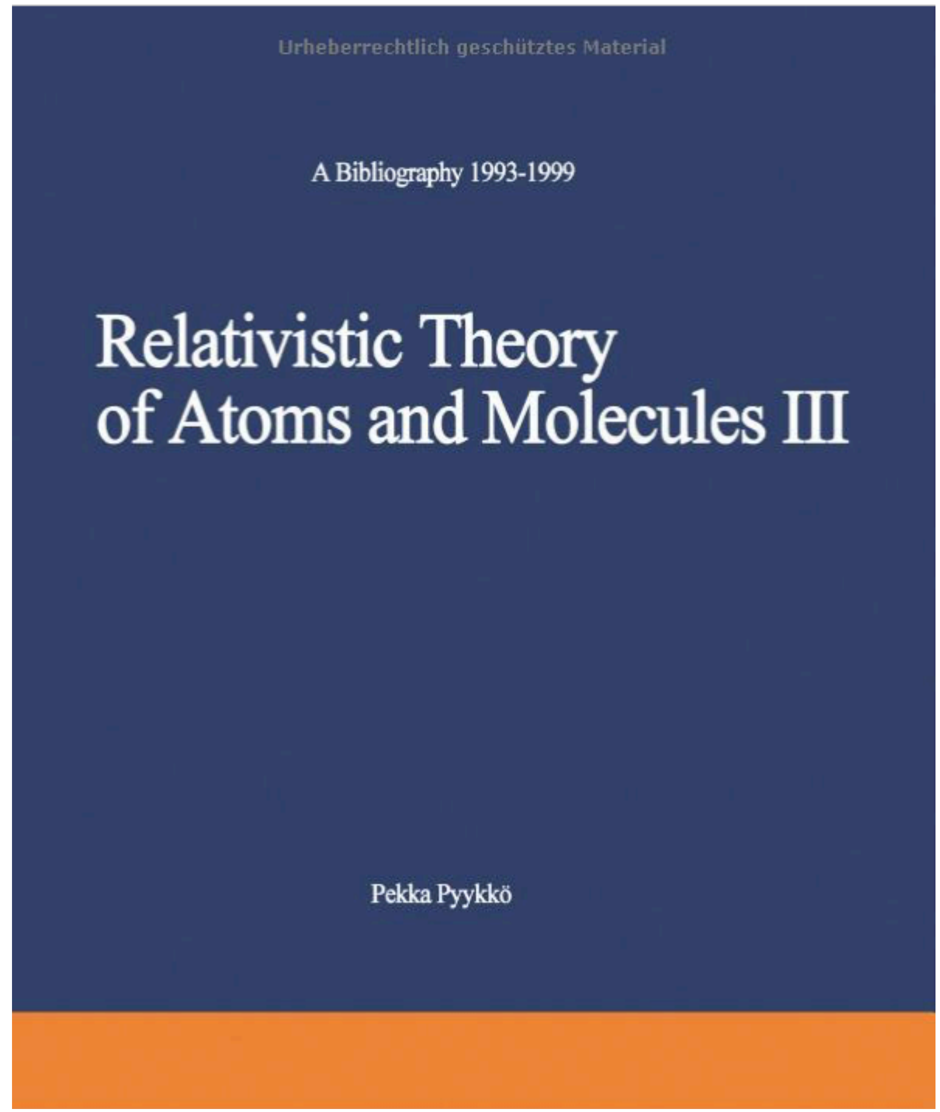
$$\boxed{u(\boldsymbol{p}, s) = \sqrt{\frac{E_N + M_N}{2M_N}} \begin{pmatrix} 1 \\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{E_N+M_N} \end{pmatrix}}$$

- Spin degree of freedom
- Antiparticles
- Small components

Atomic/Molecular systems

relativistic quantum chemistry





Relativistic corrections in heavy Atoms

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

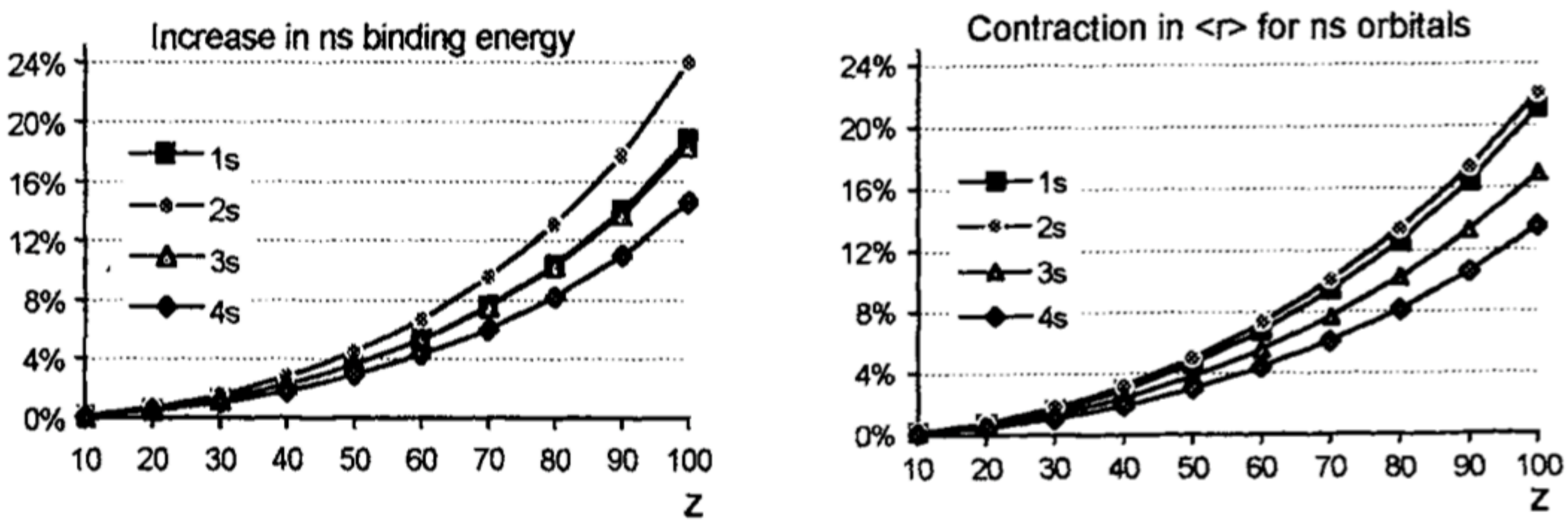
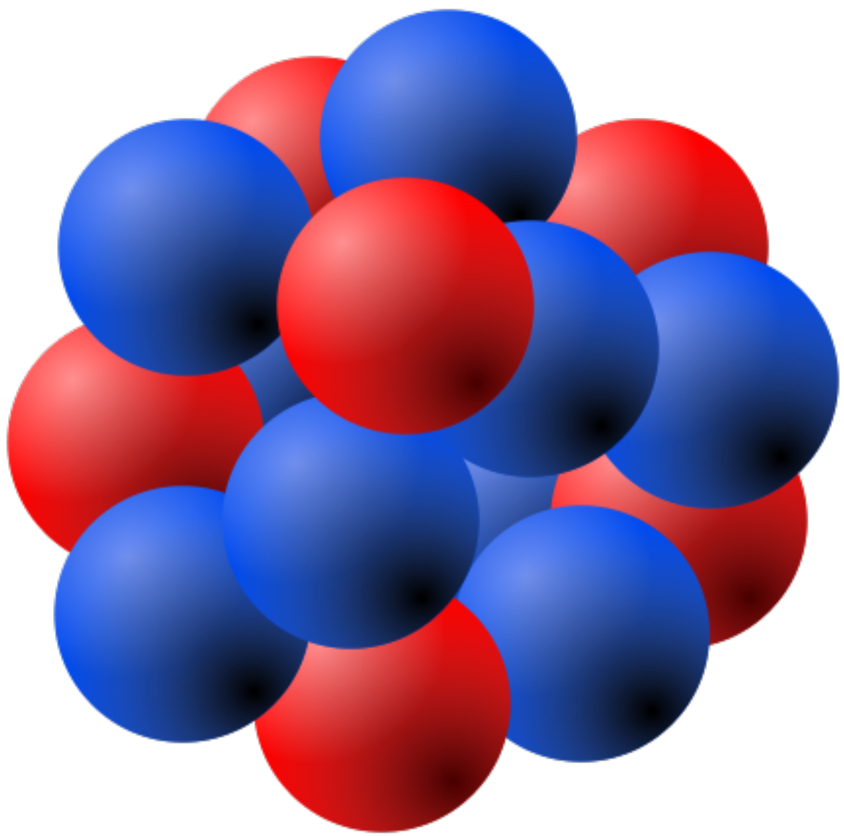


Fig. 2. Relativistic corrections for hydrogenic s orbitals (as percentage of the non relativistic value).

Relativistic Electronic Structure Theory, P. Schwerdtfeger

Nuclear (multi-nucleon) Systems

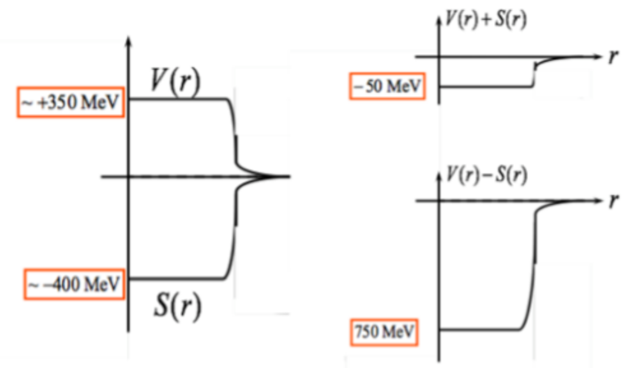


CDFT: a short summary

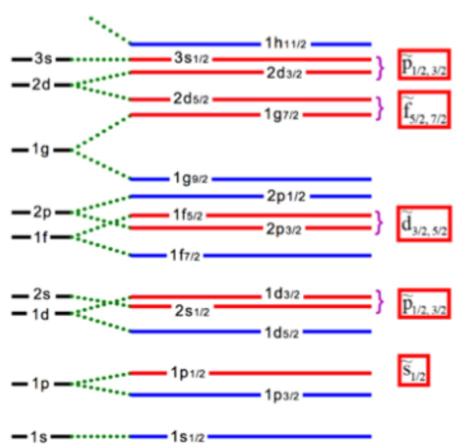
Why Covariant?

P. Ring Physica Scripta, T150, 014035 (2012)

- ✓ Spin-orbit automatically included
- ✓ Lorentz covariance restricts parameters
- ✓ Pseudo-spin Symmetry
- ✓ Connection to QCD: big V/S ~ ±400 MeV
- ✓ Consistent treatment of time-odd fields
- ✓ Relativistic saturation mechanism
- ✓ … Liang, Meng, Zhou, Physics Reports **570** : 1-84 (2015).



Pseudospin symmetry



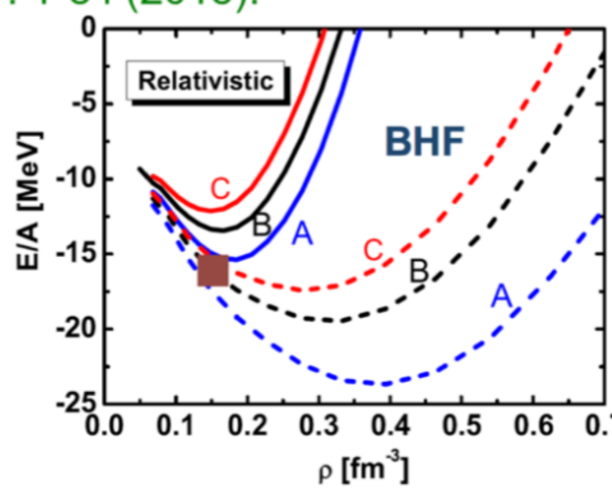
$$\begin{array}{lll} n-1, & l+2, & j=l+3/2 \\ n, & l, & j=l+1/2 \end{array}$$

$$\begin{array}{ll} \text{pseudo-orbit} : & \tilde{l}=l+1 \\ \text{pseudo-spin} : & \tilde{s}=1/2 \end{array}$$

Hecht & Adler NPA137(1969)129

Arima, Harvey & Shimizu PLB 30(1969)517

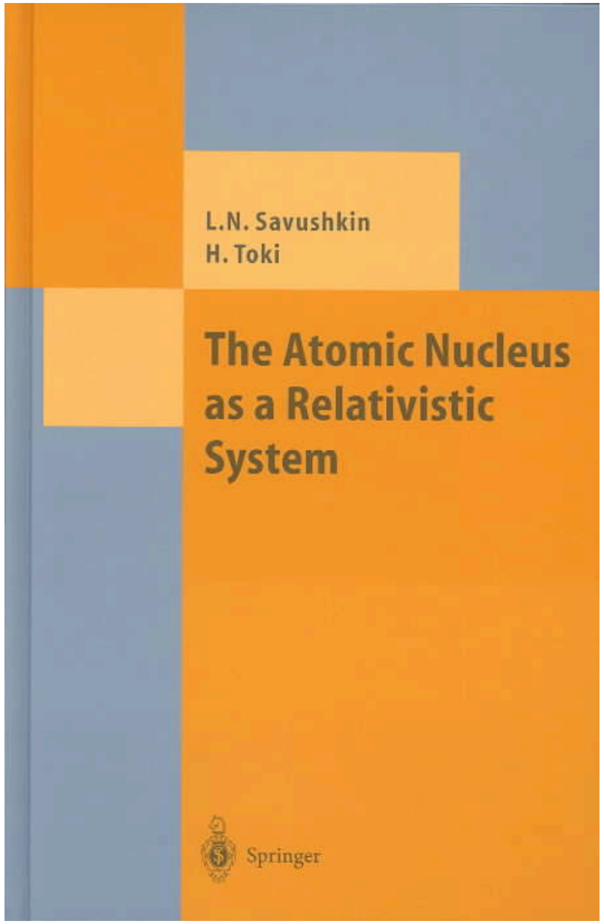
Ginocchio PRL 78, 436

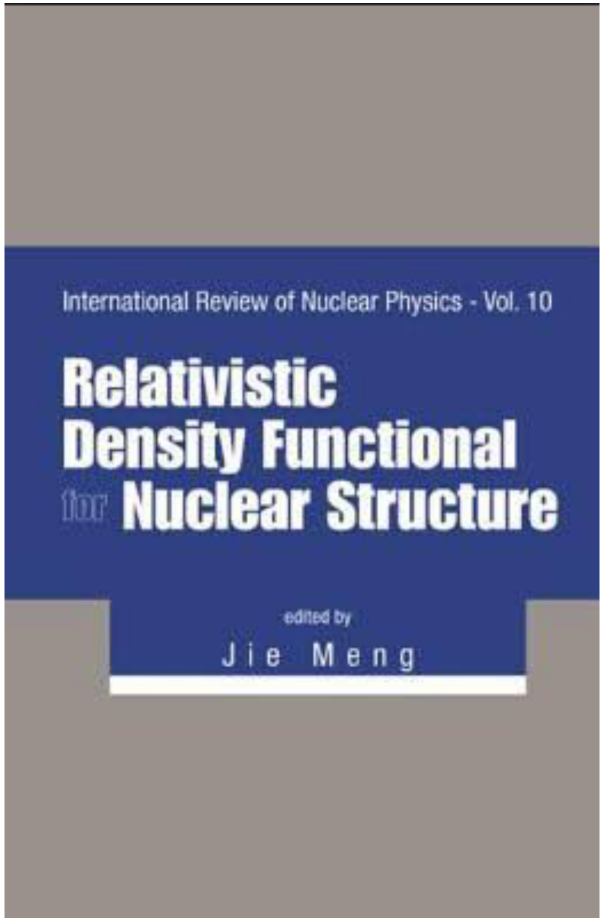


Brockmann & Machleidt, PRC42, 1965 (1990)

from Jie Meng's talk

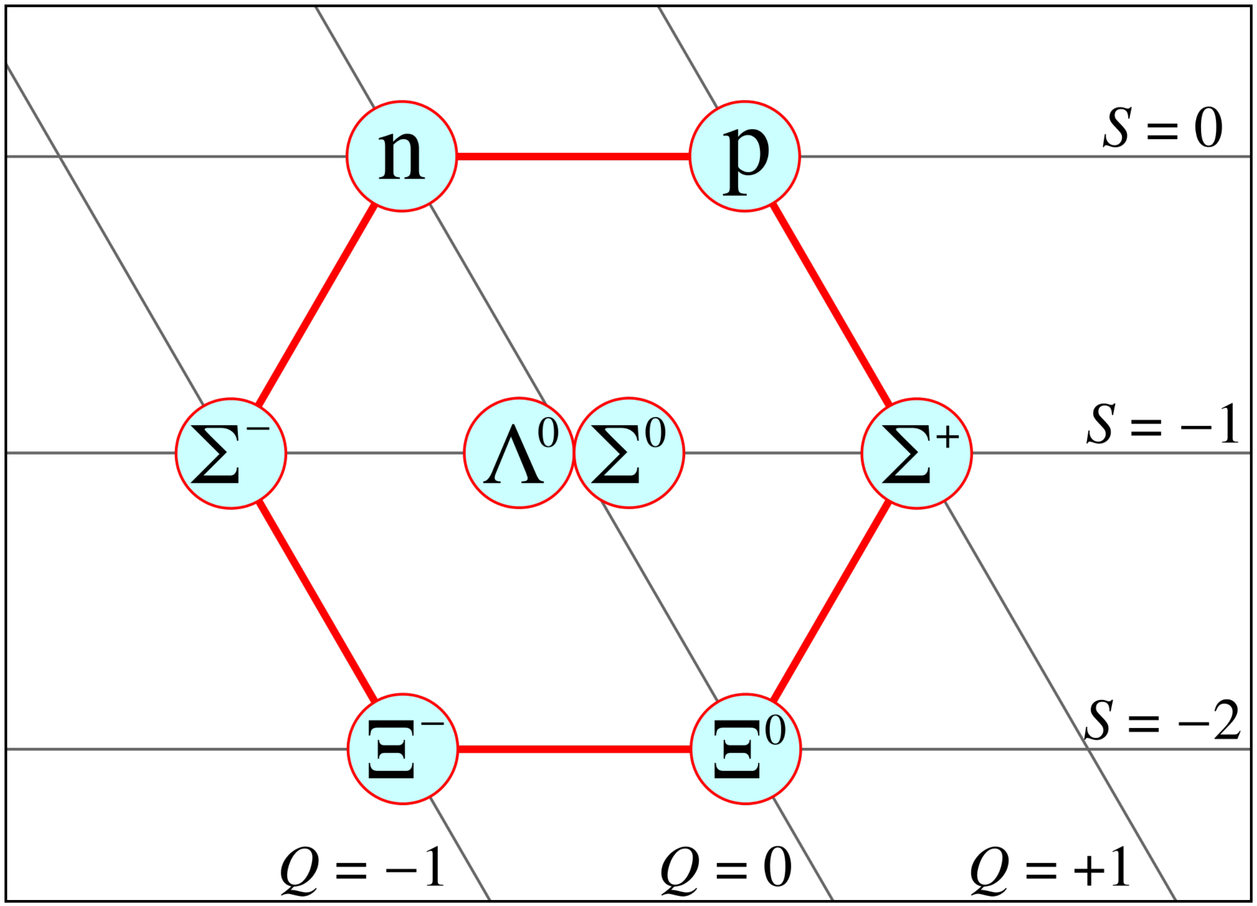
Two nice books





One-Baryon Sector

A covariant formulation of **BChPT** is essential



- Masses
- Magnetic moments
- axial and vector form factors

Chiral Perturbation Theory (ChPT)

ChPT: a low energy effective field theory of QCD

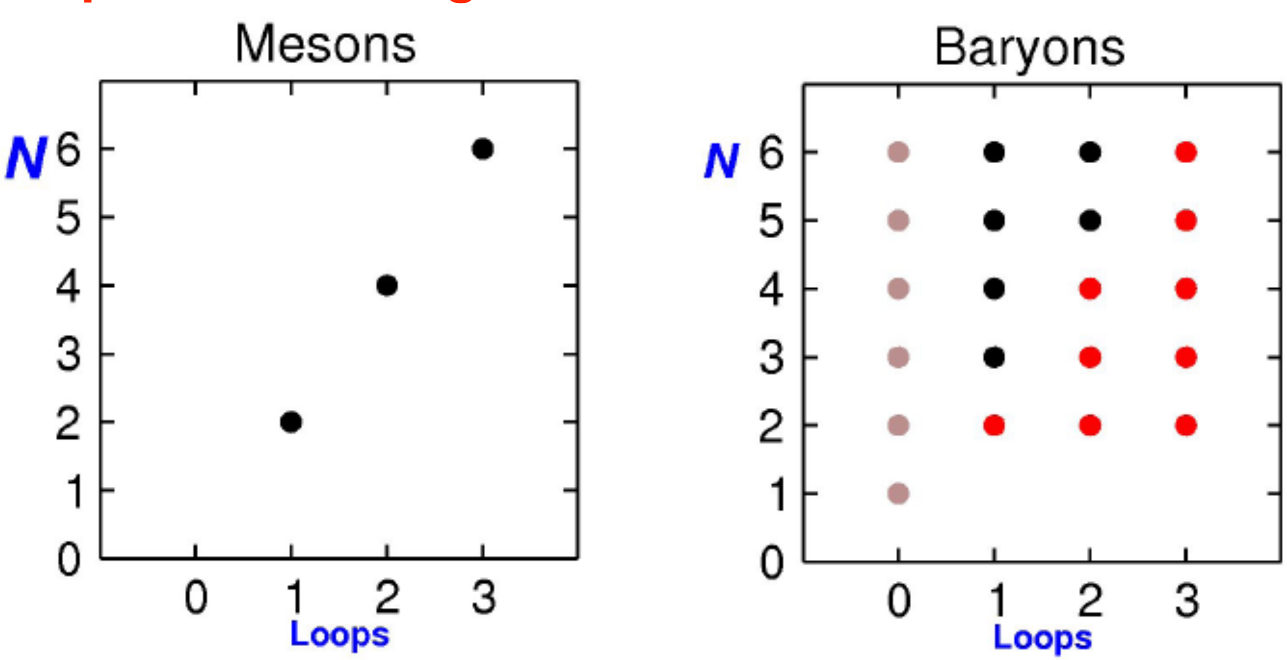
- Maps quark (u, d, s) dof’s to those of the asymptotic states, hadrons
- Perturbative formulation of low energy QCD in powers of the external momenta and the light quark masses, by utilizing chiral symmetry and its breaking pattern

Development (trilogy)

- 1979, Weinberg
- 1989, to the one-baryon sector, Gasser & Leutwyler
- 1990/91, to NN, Weinberg

Power-counting-breaking (PCB)

- **ChPT very successful in the study of Nanbu-Goldstone boson self-interactions. (at least in SU(2))**
- **In the one-baryon sector, things become problematic because of the nonzero (large) baryon mass in the chiral limit, which leads to the fact that high-order loops contribute to lower-order results, i.e., a systematic power counting is lost!**



***red dots* denote possible PCB terms (pion-nucleon scattering)**

J. Gasser et al., NPB 307, 779(1988)

$\boxed{\text{Chiral order} = 4L - 2N_M - N_B + \sum_k kV_k}$

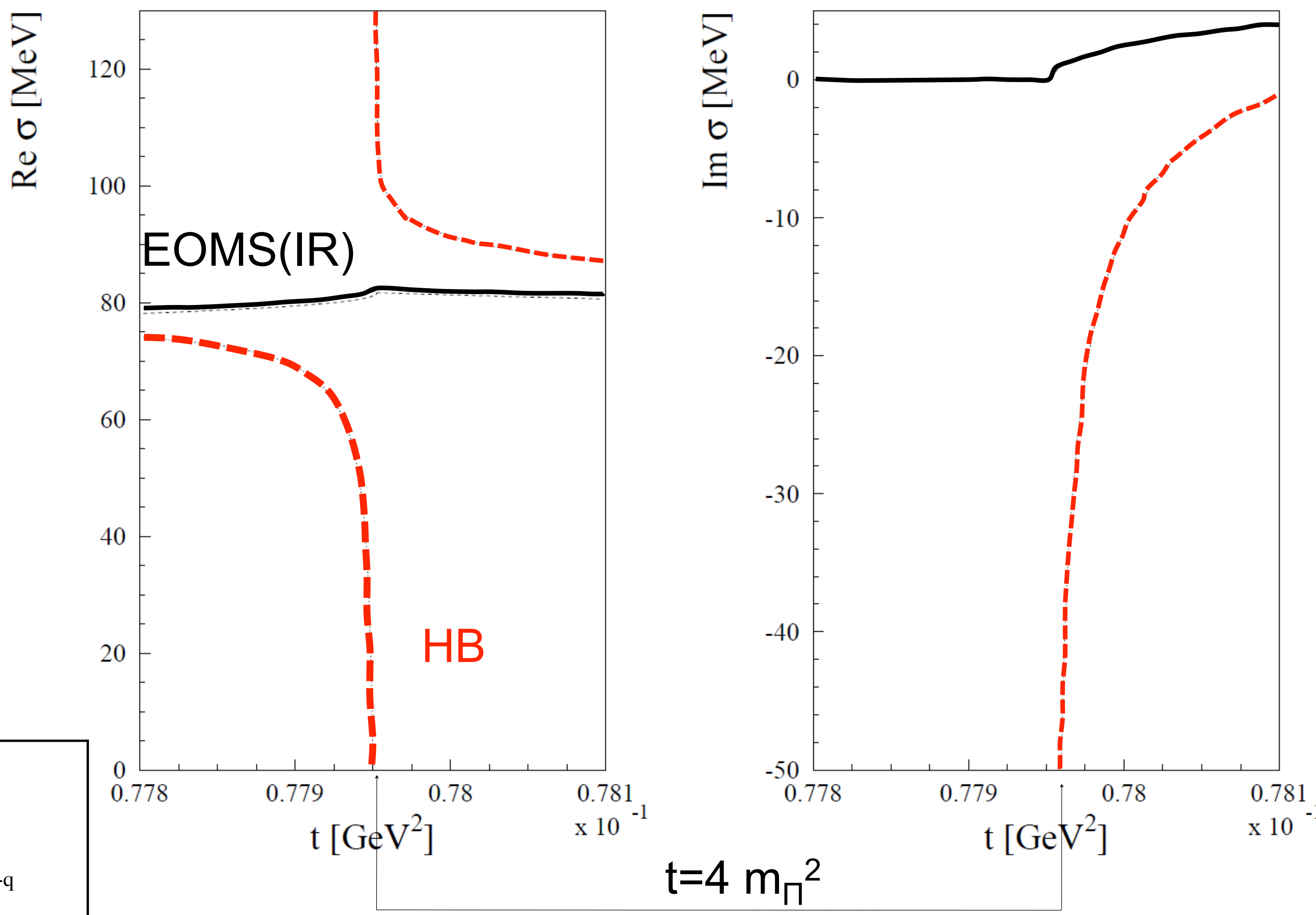
HB vs. Infrared vs. EOMS (fully covariant)

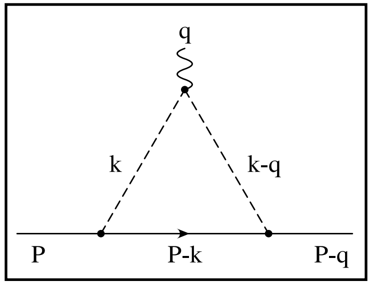
- Heavy baryon (HB) ChPT
  - non-relativistic
  - breaks analyticity of loop amplitudes
  - converges slowly (particularly in three-flavor sector)
  - strict PC and simple nonanalytical results
- Infrared BChPT
  - breaks analyticity of loop amplitudes
  - converges slowly (particularly in three-flavor sector)
  - analytical terms the same as HBChPT
- Extended-on-mass-shell (EOMS) BChPT
  - satisfies all symmetry and analyticity constraints
  - converges relatively faster--an appealing feature

The nucleon scalar form factor at q^3

$$\boxed{\langle p(p',s')|\mathcal{H}_{\rm sb}(0)|p(p,s)\rangle = \bar{u}(p',s')u(p,s)\sigma(t), \quad t=(p'-p)^2}$$

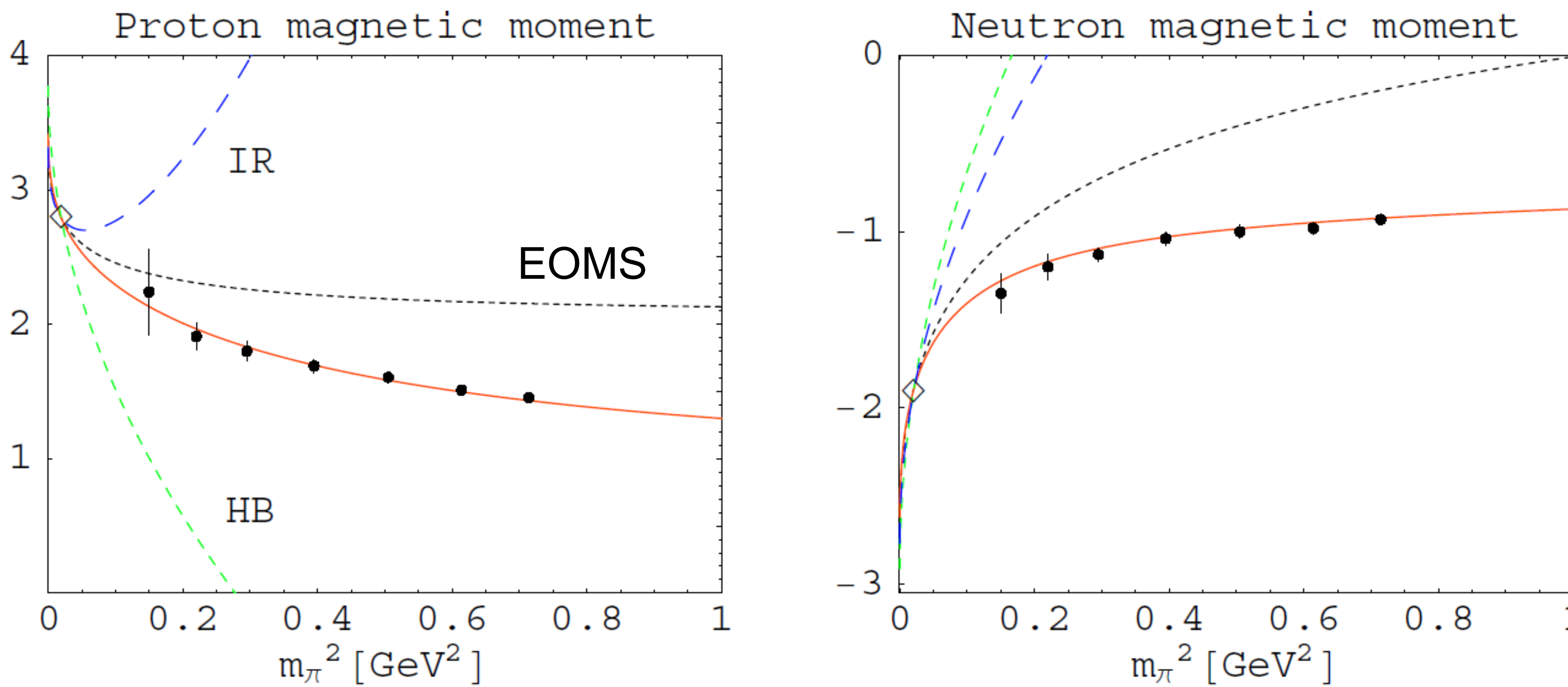
$$\mathcal{H}_{\rm sb} = \hat{m}(\bar{u}u + \bar{d}d)$$





S. Scherer, Prog.Part.Nucl.Phys.64:1-60,2010

Proton and neutron magnetic moments: chiral extrapolation



V. Pascalutsa et al., Phys.Lett.B600:239-247,2004.

Octet baryon magnetic moments at NLO BChPT

$$\chi^2 = \sum(\mu_{th} - \mu_{exp})^2$$

		p	n	Λ	Σ^-	Σ^0	Σ^+	Ξ^-	Ξ^0	$\Lambda\Sigma^0$	χ^2
LO	C-G	2.56	-1.60	-0.80	-0.97	0.80	2.56	-0.97	-1.60	1.38	**0.46**
NLO	HB	3.01	-2.62	-0.42	-1.35	0.42	2.18	-0.52	-0.70	1.68	**1.01**
	IR	2.08	-2.74	-0.64	-1.13	0.64	2.41	-1.17	-1.45	1.89	**1.83**
	EOMS	2.58	-2.10	-0.66	-1.10	0.66	2.43	-0.95	-1.27	1.58	**0.18**
	Exp.	2.79	-1.91	-0.61	-1.16	—	2.46	-0.65	-1.25	1.61	—

- Contribution of the chiral series [LO(1+NLO/LO)]:

$$\mu_p = 3.47(1-0.257), \quad \mu_n = -2.55(1-0.175), \quad \mu_\Lambda = -1.27(1-0.482),$$

$$\mu_{\Sigma^-} = -0.93(1+0.187), \quad \mu_{\Sigma^+} = 3.47(1-0.300), \quad \mu_{\Sigma^0} = 1.27(1-0.482),$$

$$\mu_{\Xi^-} = -0.93(1+0.025), \quad \mu_{\Xi^0} = -2.55(1-0.501), \quad \mu_{\Lambda\Sigma^0} = 2.21(1-0.284).$$

LSG, J. Martin Camalich , L. Alvarez-Ruso, M.J. Vicente Vacas, Phys.Rev.Lett. 101:222002,2008

Some successful applications of covariant BChPT (in the three-flavor sector)

- **Magnetic moments**

  PRL101:222002,2008; PLB676:63,2009; PRD80:034027,2009

- **Masses and sigma terms**

  PRD82:074504,2010; PRD84:074024,2011; JHEP12:073,2012; PRD 87:074001,2013; PRD89:054034,2014 ; EPJC74:2754,2014 ; PRD91:051502,2015

- **Vector form factors (couplings)**

  PRD79:094022,2009； PRD89:113007,2014

- **Axial form factors (couplings)**

  PRD78:014011,2008； PRD90:054502,2014

Recent developments in SU(3) covariant baryon chiral perturbation theory
Li-sheng Geng, Front.Phys.(Beijing) 8 (2013) 328-348

Towards a relativistic nuclear force

Our strategy

- **We construct the kernel potentials from the covariant chiral Lagrangians**

$$\begin{aligned}\mathcal{L}_{NN}^{(0)} &= -\frac{1}{2}\left[C_S(\bar\Psi\Psi)(\bar\Psi\Psi)+C_A(\bar\Psi\gamma_5\Psi)(\bar\Psi\gamma_5\Psi)\right.\\ &+ C_V(\bar\Psi\gamma_\mu\Psi)(\bar\Psi\gamma^\mu\Psi)+C_{AV}(\bar\Psi\gamma_\mu\gamma_5\Psi)(\bar\Psi\gamma^\mu\gamma_5\Psi)\\ &+ \left.C_T(\bar\Psi\sigma_{\mu\nu}\Psi)(\bar\Psi\sigma^{\mu\nu}\Psi)\right],\end{aligned}$$

5 LECs

$$\begin{aligned}\mathcal{L}_{\pi\pi}^{(2)} &= \frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu U\partial^\mu U^\dagger+(U+U^\dagger)m_\pi^2\right],\\ \mathcal{L}_{\pi N}^{(1)} &= \bar\Psi\left[i\not{D}-M_N+\frac{g_A}{2}\gamma^\mu\gamma_5 u_\mu\right]\Psi,\end{aligned}$$

- **We retain the full form of the Dirac spinors**

$$u(\boldsymbol{p},s)=\sqrt{\frac{E_N+M_N}{2M_N}}\begin{pmatrix}1\\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{E_N+M_N}\end{pmatrix}$$

NN force at leading order

- **Feynman diagrams at LO**

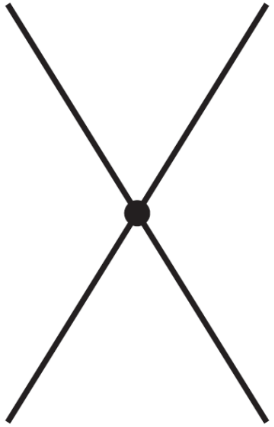
Contact Potential (CTP) One-Pion Exchange Potential (OPEP)

- **"Covariant power counting"— key to an EFT**

$$n_\chi = 4L - 2N_\pi - N_n + \sum_k kV_k,$$

Expansion parameters:
pseudscalar meson masses or small three-momenta of nucleons

NN force at leading order



Explicitly covariant form

$$u(\boldsymbol{p}, s) = \sqrt{\frac{E_N + M_N}{2M_N}} \begin{pmatrix} 1 \\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{E_N+M_N} \end{pmatrix}$$

$$\begin{aligned} V_{\rm CTP} &= C_S(\bar{u}_1 u_1)(\bar{u}_2 u_2) + C_A(\bar{u}_1\gamma_5 u_1)(\bar{u}_2\gamma_5 u_2) \\ &+ C_V(\bar{u}_1\gamma_\mu u_1)(\bar{u}_2\gamma^\mu u_2) \\ &+ C_{AV}(\bar{u}_1\gamma_\mu\gamma_5 u_1)(\bar{u}_2\gamma^\mu\gamma_5 u_2) \\ &+ C_T(\bar{u}_1\sigma_{\mu\nu} u_1)(\bar{u}_2\sigma_{\mu\nu} u_2), \end{aligned}$$

Expressed in terms of pauli matrices

$$\begin{aligned} V_{\rm CTP} = \sum_{i=S,A,V,AV,T} C_i \Big[& V_C^i(E_N) + V_\sigma^i(E_N)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + V_{SO}^i(E_N)\frac{i}{2}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot(\boldsymbol{k}\times\boldsymbol{q}) \\ & + V_{\sigma q}^i(E_N)\boldsymbol{\sigma}_1\cdot\boldsymbol{q}\boldsymbol{\sigma}_2\cdot\boldsymbol{q} + V_{\sigma k}^i(E_N)\boldsymbol{\sigma}_1\cdot\boldsymbol{k}\boldsymbol{\sigma}_2\cdot\boldsymbol{k} \\ & + V_{\sigma L}^i(E_N)\boldsymbol{\sigma}_1\cdot(\boldsymbol{q}\times\boldsymbol{k})\boldsymbol{\sigma}_2\cdot(\boldsymbol{q}\times\boldsymbol{k})\Big]. \end{aligned}$$

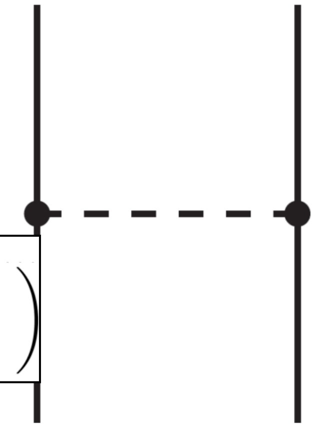
Energy dependence!

- **all allowed six spin operators,**

Non-relativistic (static) limit

$$V_{\rm CTP}^{\rm NonRel.} = \boxed{-(C_S + C_V)} + \boxed{(C_{AV} - 2C_T)}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \mathcal{O}\left(\frac{1}{M_N}\right).$$

NN force at leading order



Explicitly covariant form

$$u(\boldsymbol{p}, s) = \sqrt{\frac{E_N + M_N}{2M_N}} \begin{pmatrix} 1 \\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{E_N+M_N} \end{pmatrix}$$

$$V_{\mathrm{OPEP}} = \xi_{N_1N_2\to N_3N_4} \frac{g_A^2}{4f_\pi^2} \frac{(\bar{u}_4\gamma^\mu\gamma_5 q_\mu u_2)(\bar{u}_3\gamma^\nu\gamma_5 q_\nu u_1)}{\boldsymbol{q}^2 + m_\pi^2}.$$

Expressed in terms of pauli matrices and NR wfs

$$\begin{aligned} V_{\mathrm{OPEP}} &= \frac{g_A^2}{4f_\pi^2} \frac{1}{\boldsymbol{q}^2 + m_\pi^2 + i\epsilon} [V_{\sigma q}(E_N) \boldsymbol{\sigma_1} \cdot \boldsymbol{q} \boldsymbol{\sigma_2} \cdot \boldsymbol{q} \\ &\quad + V_C(E_N) + U_\sigma \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + V_{SO}(E_N) \frac{i}{2}(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{k} \times \boldsymbol{q}) \\ &\quad + V_{\sigma k}(E_N) \boldsymbol{\sigma}_1 \cdot \boldsymbol{k} \boldsymbol{\sigma}_2 \cdot \boldsymbol{k} + V_{\sigma L}(E_N) \boldsymbol{\sigma}_1 \cdot (\boldsymbol{q} \times \boldsymbol{k}) \boldsymbol{\sigma}_2 \cdot (\boldsymbol{q} \times \boldsymbol{k})] \end{aligned}$$

Non-relativistic (static) limit

$$V_{\mathrm{OPEP}}^{\mathrm{NonRel.}} = -\frac{g_A^2}{4f_\pi^2} \boxed{\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{q} \boldsymbol{\sigma}_2 \cdot \boldsymbol{q}}{\boldsymbol{q}^2 + m_\pi^2 + i\epsilon} + \mathcal{O}(\frac{1}{M_N})$$

A hint at a more efficient formulation

$$
\begin{aligned}
V_{1S0} \;=\; & 4\pi \left[C_{1S0} + (C_{1S0} + \hat{C}_{1S0}) \underline{\left(\frac{\vec{p}^2 + \vec{p}'^2}{4M_N^2} + \cdots \right)} \right] \\
& - \frac{3\pi g_A^2}{f_\pi^2} \int_{-1}^{1} \frac{dz}{\vec{q}^2 + m_\pi^2} \left[\vec{q}^2 - \underline{\left(\frac{(\vec{p}^2 - \vec{p}'^2)^2}{4M_N^2} + \cdots \right)} \right] \qquad (18)
\end{aligned}
$$

$$
\begin{aligned}
C_{1S0} &= (C_S + C_V + 3C_{AV} - 6C_T), \\
\hat{C}_{1S0} &= (3C_V + C_A + C_{AV} + 6C_T),
\end{aligned}
$$

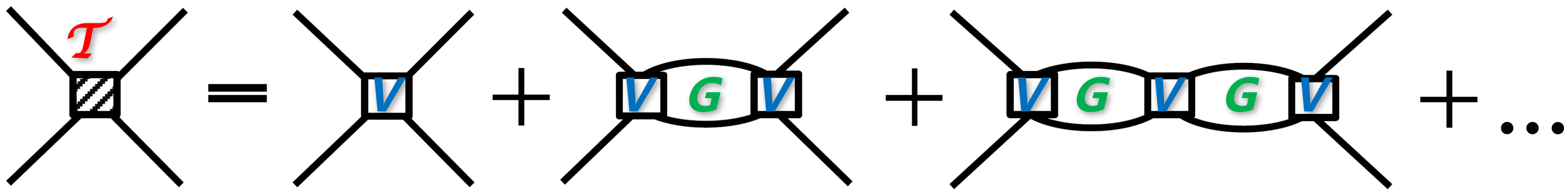
A large contribution of the correction terms is essential to describe the 1S0 phase shift

J. Soto and J. Tarrus, Phys. Rev. C78, 024003 (2008).

B. Long, Phys. Rev. C88, 014002 (2013).

The nuclear force is non-perturbative

Non-perturbative summation of the tree-level potential



3D reduction of the Bethe-Salpeter equation (Kadyshevsky)

$$T(p',p) = V(p',p) + \int_0^{+\infty} \frac{k^2 dk}{(2\pi)^3} V(p',k) \frac{2\pi M_N^2}{(k^2+M_N^2)(\sqrt{p^2+M_N^2}-\sqrt{k^2+M_N^2}+i\epsilon)} T(k,p).$$

With the implicit mass "on-shell" approximation of the potential.

$$E_p = \sqrt{M_N^2 + \vec{p}^{\,2}},$$

NN force at leading order

- **5 LECs to fit the np phase shifts of Nijmegen 93**
  - **7** partial waves: ***J=0, 1*** $^1S_0,\ ^3P_0,\ ^1P_1,\ ^3P_1,\ ^3D_1,\ ^3S_1,\ \epsilon_1$
  - **42** data points: 6 data points for each partial wave
  - $(E_{\rm lab} = 1,\ 5,\ 10,\ 25,\ 50,\ 100\ \mathrm{MeV})$

$$\tilde{\chi}^2 = \sum_i \left(\delta_i^{\rm Theory} - \delta_i^{\rm Nij93}\right)^2$$

- **Cutoff renormalization in solving the scattering eq.**

$$V(p', p) \to V(p', p)\boldsymbol{f(p', p)} \quad f(p', p) = \exp[-(p'/\Lambda)^{2n} - (p/\Lambda)^{2n}]$$

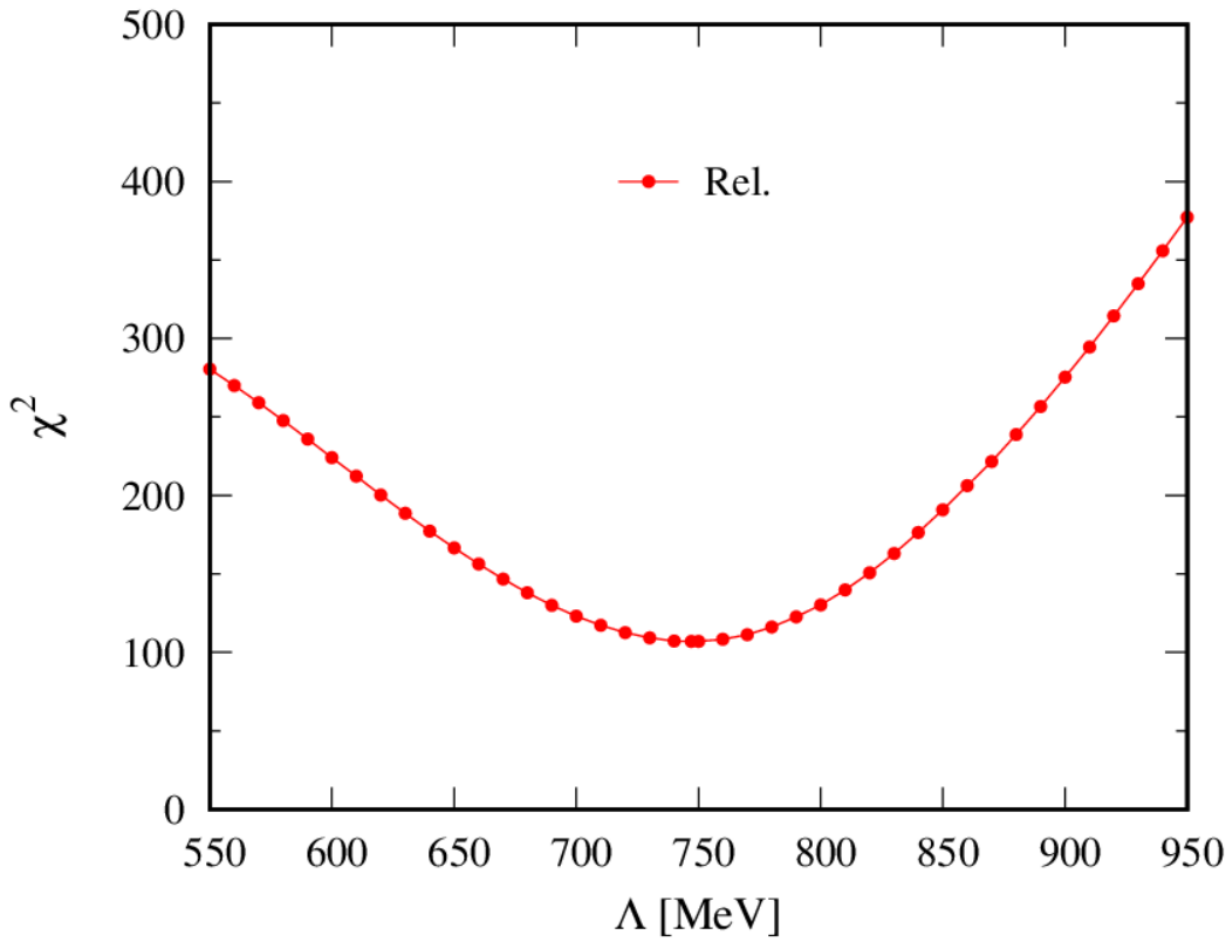
Two remarks

😃 Potential is fully covariant

😞 Scattering amplitude is not fully covariant, because of the use of the Kadyshevsky equation and the regulating form factor

Best fit as a function of the cutoff

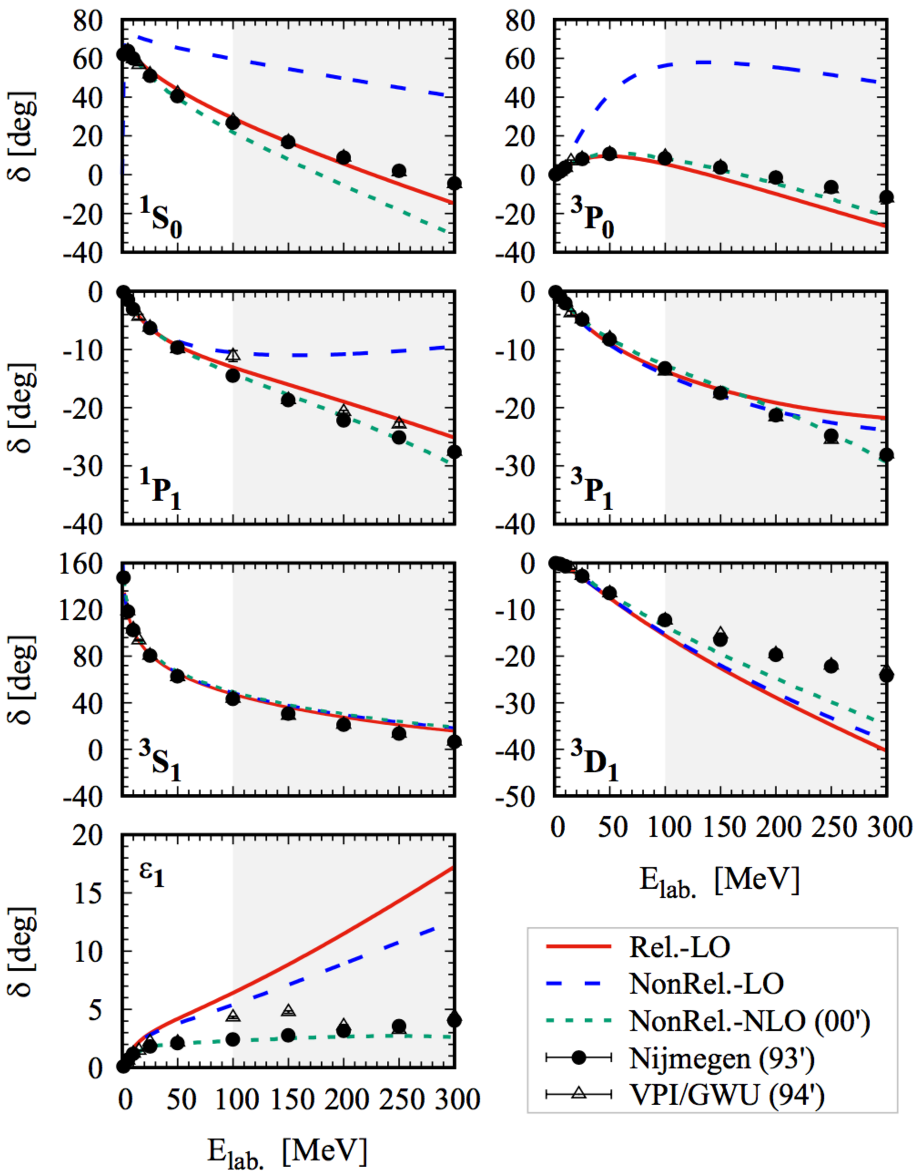
$$f(p', p) = \exp[-(p'/\Lambda)^{2n} - (p/\Lambda)^{2n}]$$



LECs	Values $[10^4\ \mathrm{GeV}^{-2}]$
C_S	0.1339
C_A	-0.05477
C_V	-0.2673
C_{AV}	-0.2454
C_T	-0.06310

Λ=747 MeV, the minimum of fit-χ^2=106.90, χ^2/d.o.f. = 2.89

A closer look at the partial waves



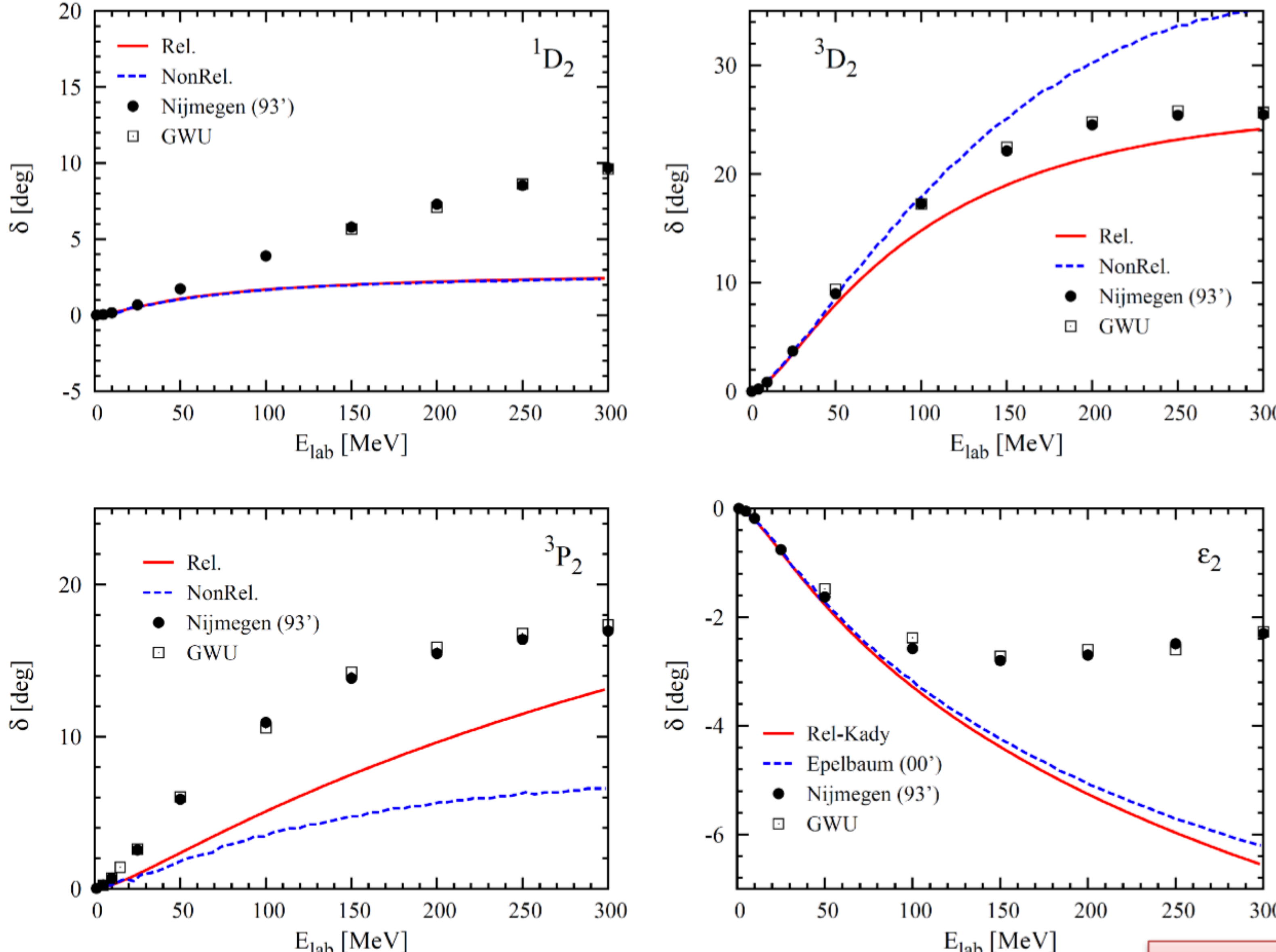
- **Improved description** of $^1S_0$ $^3P_0$, $^1P_1$ phase shifts
- **Quantitatively similar** with the non relativistic case for J=1 partial waves

Relativistic vs. non-relativistic Very promising

	Relativistic Chiral NF	**Non-relativistic Chiral NF**	
Chiral order	LO	LO	NLO*
No. of LECs	5	2	9
χ^2**/d.o.f.**	**2.9**	**147.9**	**2.5**

A more efficient description is achieved

Higher partial waves remain the same



Λ_F=600 MeV

OPE prediction

BbS vs. Kadeshevsky scattering equation

BbS(Blankenbecler-Sugar) —Bonn potential

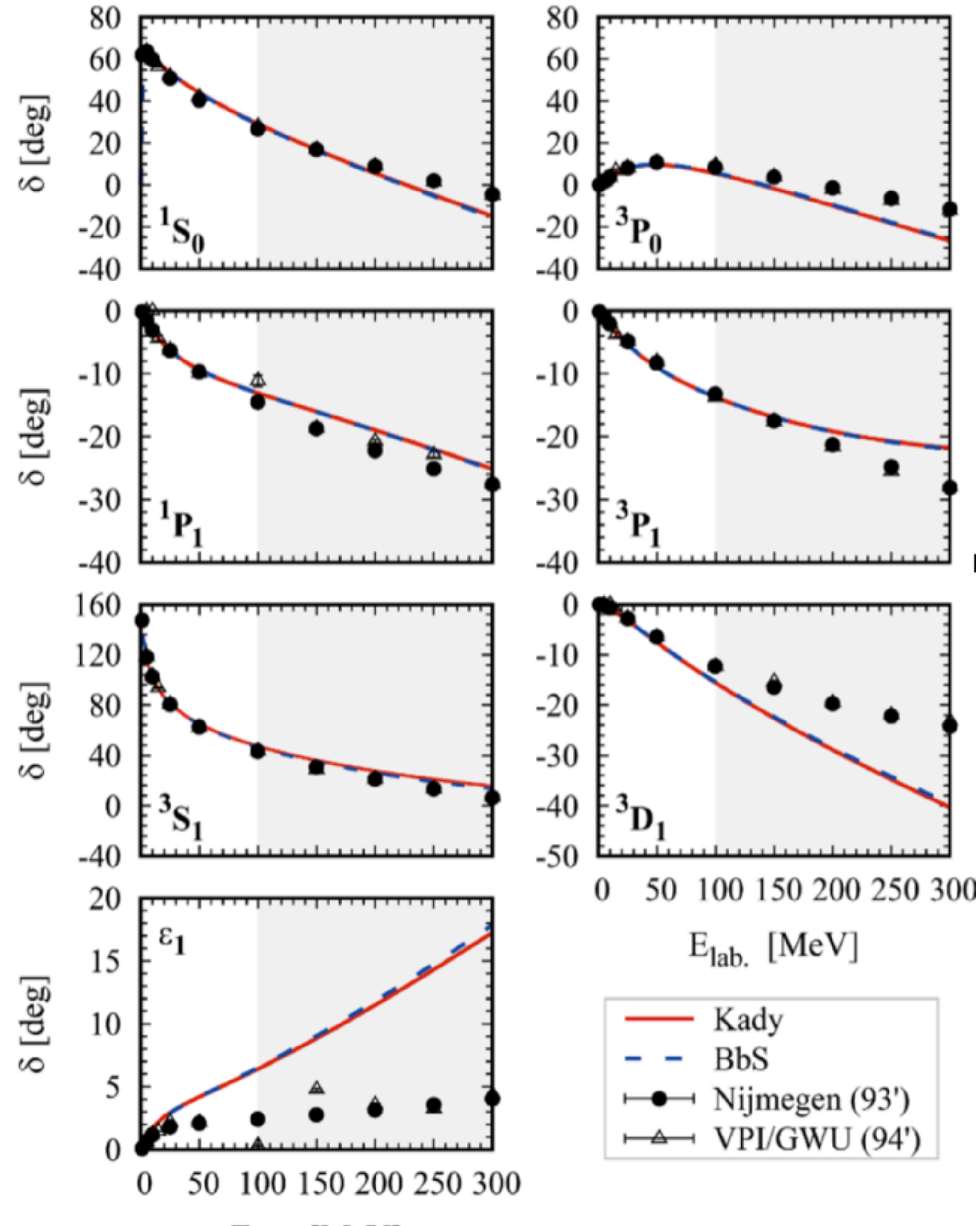
- Replace the scattering function from the **Kadyshevsky** eq. to the **Blankenbecler-Sugar** eq.

$$T(p',p) = V(p',p) + \int_0^{+\infty} \frac{dk}{(2\pi)^3} V(p',k) \times M_N^2 \frac{1}{\sqrt{k^2 + M_N^2(p^2-k^2)+i\epsilon}} T(k,p).$$

R.Blankenbecler, Phys.Rev.(1966)

- Best fit results:

	Kady.	BbS
Cutoff Λ [MeV]	**747**	**743**
Fit-χ^2/d.o.f.	**2.9**	**2.5**



Deuteron Properties and scattering lengths

in reasonable agreement with data

- Deuteron binding energy

	Expt.	Kady.	BbS
B_d [MeV]	2.22457	**1.86700**	**1.93900**

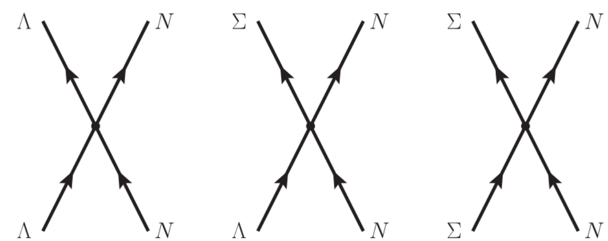
- *S*-wave scattering length

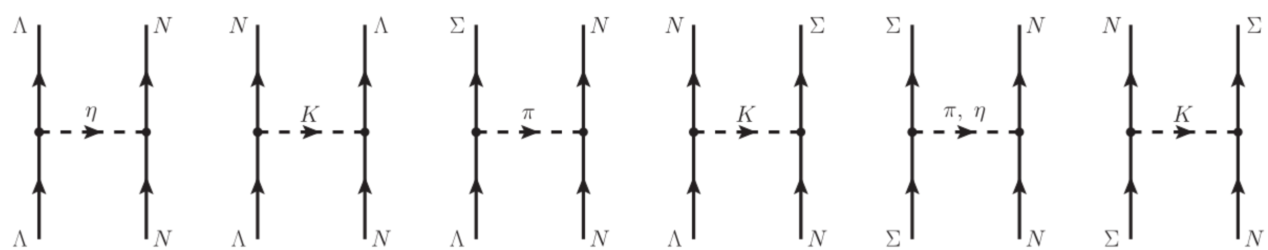
	Expt.	Kady.	BbS
a_{1S0} [fm]	-23.739	**-20.299**	**-20.415**
a_{3S1} [fm]	5.420	**5.746**	**5.667**

ΛN and ΣN system (S = -1, I = 3/2, 1/2)

$\Sigma^+ p$	Λp, $\Sigma^+ n$, $\Sigma^0 p$	Λn, $\Sigma^0 n$, $\Sigma^- p$	$\Sigma^- n$	
+3/2	+1/2	-1/2	-3/2	$\leftarrow I_3$

Contact





One-meson-exchange

ΛN and ΣN systems (S = -1, I = 3/2, 1/2)

Four-baryon contact terms

$$\mathcal{L}^1_{\rm CT} = C^1_i \left\langle \bar{B}_a \bar{B}_b (\Gamma_i B)_b (\Gamma_i B)_a \right\rangle \quad \mathcal{L}^2_{\rm CT} = C^2_i \left\langle \bar{B}_a (\Gamma_i B)_a \bar{B}_b (\Gamma_i B)_b \right\rangle \quad \mathcal{L}^3_{\rm CT} = C^3_i \left\langle \bar{B}_a (\Gamma_i B)_a \right\rangle \left\langle \bar{B}_b (\Gamma_i B)_b \right\rangle$$

Clifford algebra: $\Gamma_1 = 1, \quad \Gamma_2 = \gamma^\mu, \quad \Gamma_3 = \sigma^{\mu\nu}, \quad \Gamma_4 = \gamma^\mu \gamma_5, \quad \Gamma_5 = \gamma_5.$

12 LECS

	$C^{\Lambda\Lambda}_{1S0}$	$\hat{C}^{\Lambda\Lambda}_{1S0}$	$C^{\Sigma\Sigma}_{1S0}$	$\hat{C}^{\Sigma\Sigma}_{1S0}$	
$C^{\Lambda\Lambda}_{3S1}$	$\hat{C}^{\Lambda\Lambda}_{3S1}$	$C^{\Sigma\Sigma}_{3S1}$	$\hat{C}^{\Sigma\Sigma}_{3S1}$	$C^{\Lambda\Sigma}_{3S1}$	$\hat{C}^{\Lambda\Sigma}_{3S1}$
		$C^{\Lambda\Lambda}_{3P1}$	$C^{\Sigma\Sigma}_{3P1}$		

Meson-baryon interaction

$$\mathcal{L}^{(1)}_{MB} = \left\langle \bar{B} \left(i \not{D} - M_B \right) B - \frac{D}{2} \bar{B} \gamma^\mu \gamma_5 \{u_\mu, B\} - \frac{F}{2} \bar{B} \gamma^\mu \gamma_5 [u_\mu, B] \right\rangle$$

Covariant derivative:

$$D^\mu B = (\partial_\mu + \Gamma_\mu - i v^{(s)}_\mu) B$$

$$B = \sum_a \frac{B_a \lambda_a}{\sqrt{2}} \equiv \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

parameter free: D=0.8 & F=0.46

Scarce scattering data of poor quality

- Poor

1. Small quantity (36, *S* = -1, YN)
2. Age-old (1960s - 1970s)
3. Poor quality (large error bar)

- R. Engelmann, et al., Phys. Lett. 21 (1966) 587
- G. Alexander, et al., Phys. Rev. 173 (1968) 1452
- B. Sechi-Zorn, et al., Phys. Rev. 175 (1968) 1735
- F. Eisele, et al., Phys. Lett. 37B (1971) 204
- V. Hepp and H. Schleich, Z. Phys. 214 (1968) 71

- Short lifetime of hyperons! (≤ 10^{-10} s)

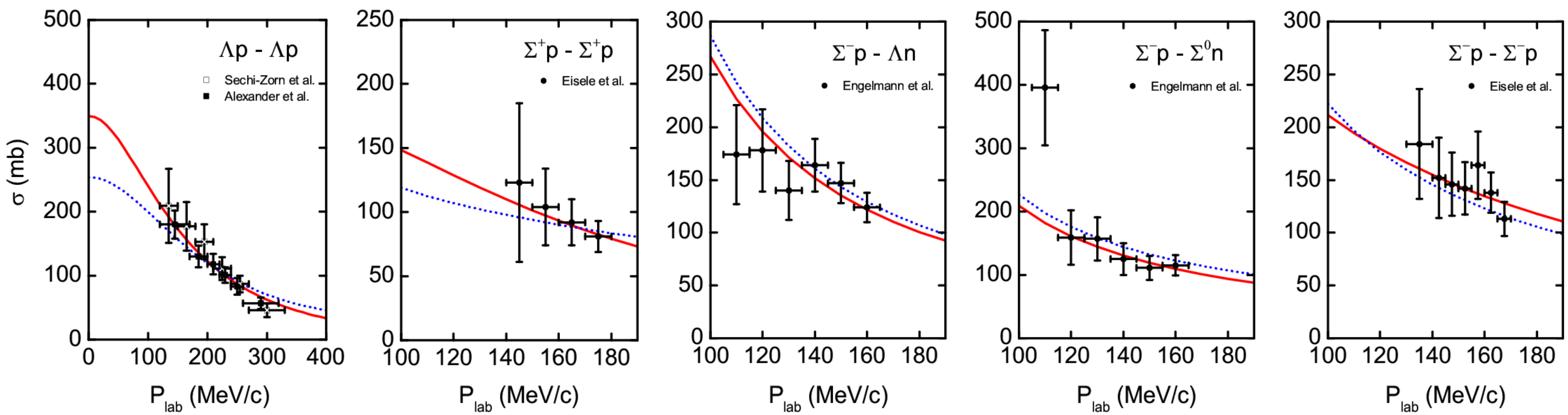
$\Lambda \to p\pi^-,\ n\pi^0 \ldots$ $\quad \Sigma^- \to n\pi^- \ldots$

$\Sigma^+ \to p\pi^0,\ n\pi^+ \ldots$ $\quad \Xi^0 \to \Lambda\pi^0 \ldots$

$\Sigma^0 \to \Lambda\gamma,\ \Lambda\gamma\gamma \ldots$ $\quad \Xi^- \to \Lambda\pi^- \ldots$

$\Lambda p \to \Lambda p$		$\Lambda p \to \Lambda p$		$\Sigma^- p \to \Lambda n$	
$p_{\rm lab}^{\Lambda}$	$\sigma_{\rm exp}$	$p_{\rm lab}^{\Lambda}$	$\sigma_{\rm exp}$	$p_{\rm lab}^{\Sigma^-}$	$\sigma_{\rm exp}$
135 ± 15	209 ± 58	145 ± 25	180 ± 22	110 ± 5	174 ± 47
165 ± 15	177 ± 38	185 ± 15	130 ± 17	120 ± 5	178 ± 39
195 ± 15	153 ± 27	210 ± 10	118 ± 16	130 ± 5	140 ± 28
225 ± 15	111 ± 18	230 ± 10	101 ± 12	140 ± 5	164 ± 25
255 ± 15	87 ± 13	250 ± 10	83 ± 13	150 ± 5	147 ± 19
300 ± 30	46 ± 11	290 ± 30	57 ± 9	160 ± 5	124 ± 14
$\Sigma^+ p \to \Sigma^+ p$		$\Sigma^- p \to \Sigma^- p$		$\Sigma^- p \to \Sigma^0 n$	
$p_{\rm lab}^{\Sigma^+}$	$\sigma_{\rm exp}$	$p_{\rm lab}^{\Sigma^-}$	$\sigma_{\rm exp}$	$p_{\rm lab}^{\Sigma^-}$	$\sigma_{\rm exp}$
145 ± 5	123 ± 62	135 ± 5	184 ± 52	110 ± 5	396 ± 91
155 ± 5	104 ± 30	142.5 ± 5	152 ± 38	120 ± 5	159 ± 43
165 ± 5	92 ± 18	147.5 ± 5	146 ± 30	130 ± 5	157 ± 34
175 ± 5	81 ± 12	152.5 ± 5	142 ± 25	140 ± 5	125 ± 25
		157.5 ± 5	164 ± 32	150 ± 5	111 ± 19
		162.5 ± 5	138 ± 19	160 ± 5	115 ± 16
		167.5 ± 5	113 ± 16		
$\Sigma^- p$ inelastic capture ratio at rest		$r_R = 0.468 \pm 0.010$			

Description of experimental data



Red solid line: Covariant ChEFT (LO) Blue dotted line: Weinberg's approach (LO)

Λ_F = 600 MeV

36 YN data	Weinberg's approach	Covariant ChEFT		NSC97f$
No. of LECs	5 (LO*)	23 (NLO#)	12 (LO)	29
χ^2	28.3	16.2	16.7	16.7

*Polinder NPA799 (2006) 244 #Haidenbauer NPA915 (2013) 24 $Rijken PRC 59 (1999) 21

Relativistic formulation seems to be more efficient!

Summary and Outlook

- ✤ Nuclear forces based on Chiral EFT have made remarkable progress in the past decade.
- ✤ Covariant descriptions of the one-baryon and nuclear systems have been quite successful as well.
- ✤ Time is mature to develop a covariant formulation of baryon-baryon forces in chiral EFT.
- ✤ Initial (first) results are very promising. The key is the covariant power counting (vs. the Weinberg power counting)
- ✤ More is coming. Remain tuned.
    - NLO, N2LO (high precision) NN
    - NLO YN, YY — connection to LQCD

Thank you very much for your attention!

Covariant BChPT in the NN case

- **E. Epelbaum, J. Gegelia, PLB716(2013)338**
  - LO, kernel potential consistent with HB, plus Kadeshevsky equaiton
- **E. Epelbaum, A.M. Gasparyan, J. Gegelia, Eur.Phys.J. A51 (2015), 71**
  - NLO contact terms treated non-perturbatively to solve 1S0 discrepancy
- **J. Behrendt, E. Epelbaum, J. Gegelia et al., 1606.01489**
  - LO: higher derivative terms added—equivalent to add form factors

EFT & ChPT Citations

- Steven Weinberg, “Phenomenological Lagrangians, ” Physica A96 (1979)327-340—**Inspire cited 2838 times**
- J. Gasser and H. Leutwyler, “Chiral Perturbation Theory to One Loop,” Annals Phys. 158 (1984)142—**Inspire cited 3595 times**
- J. Gasser and H. Leutwyler, “Chiral Perturbation Theory: Expansions in the Mass of the Strange Quark,” Nucl. Phys. B 250(1984)465—**Inspire cited 3412 times**

as of July 8th, 2016

Chiral Force Citations

- Steven Weinberg, “Nuclear forces from chiral Lagrangians,” Phys.Lett. B251 (1990) 288-292—inspire cited 1013 times
- Steven Weinberg, “Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces,” Nucl.Phys. B363 (1991) 3-18—-inspire cited 971 times
- D.R. Entem and R. Machleidt, “Accurate charge dependent nucleon nucleon potential at fourth order of chiral perturbation theory,”Phys.Rev. C68 (2003) 041001 —839 times
- E. Epelbaum, W. Glockle, Ulf-G. Meissner, “The Two-nucleon system at next-to-next-to-next-to-leading order ,” Nucl.Phys. A747 (2005) 362-424 —-452 times

as of July 8th, 2016

Weinberg Power Counting

- Potential organized by

$$\boxed{V_{\text{eff}} = V_{\text{eff}}\left(q, g, \mu\right) = \sum_{\nu} q^{\nu} \mathcal{V}_{\nu}\left(q/\mu, g\right)}$$

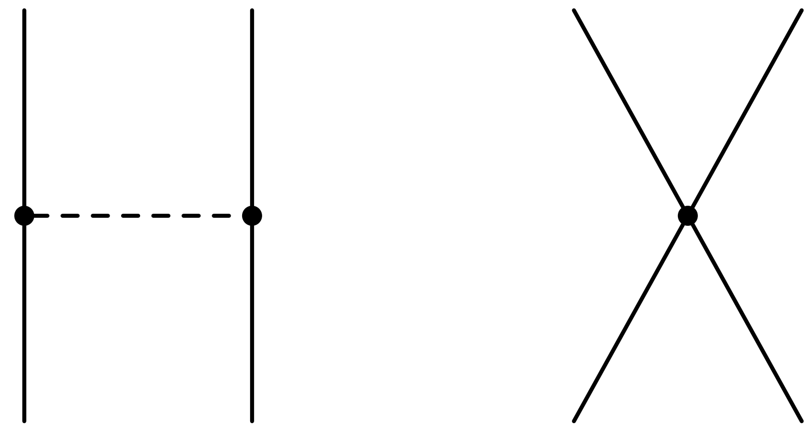
- Chiral power counting

$$\boxed{\nu = 2 - \tfrac{1}{2}B + 2L + \sum_i v_i \Delta_i \,, \qquad \Delta_i = d_i + \tfrac{1}{2} b_i - 2}$$

- B: number of external baryons
- L: number of GB loops
- ν_i: number of vertices with dimension Δ_i
  - d_i: number of derivatives or NGB masses
  - b_i: number of baryon fields in the interaction Δ_i

Leading order: $\nu=0$

- $B=4$, $L=0$, $\Delta_i=0$
  - contact: $d_i=0$; $b_i=4$
  - one pion exchange: $d_i=1$, $b_i=2$

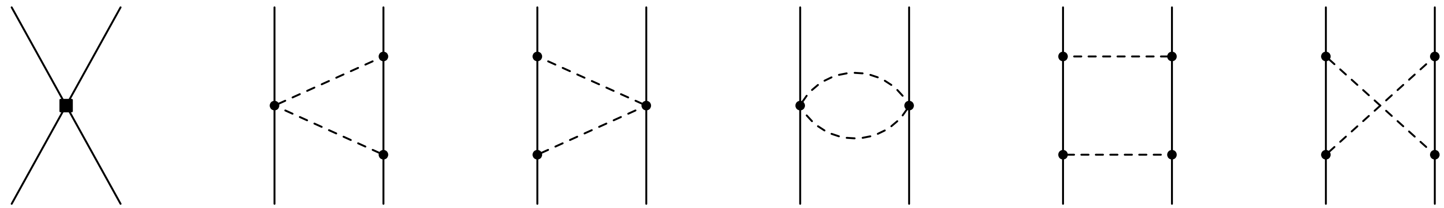


$v=1$ vanishes

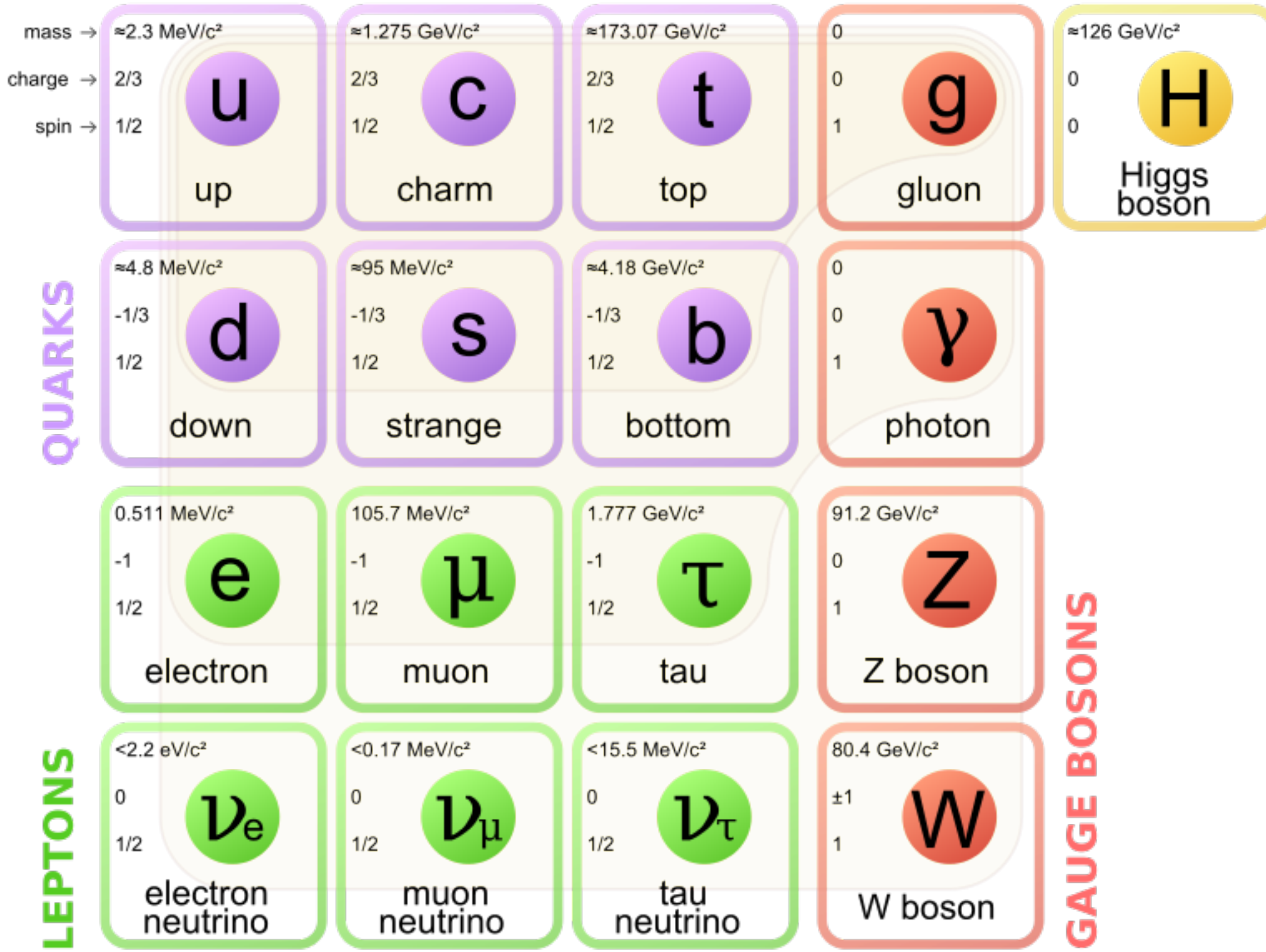
- $B=4$, $L=0$, $\Delta=1$
- Parity conservation

Next-to-leading order ν=2

- B=4, L=0, Δ_i=2 or 2x1
- B=4, L=1, Δ_i=0



Standard Model of Particle Physics



Number of parameters for the np potential

for the np potential

	Nijmegen PWA93	CD-Bonn "high precision"	NLO Q^2 (NNLO)	N^3LO Q^4 (N^4LO)	N^5LO Q^6
$^1S_0$	3	4	2	4	6
$^3S_1$	3	4	2	4	6
$^3S_1$-$^3D_1$	2	2	1	3	6
$^1P_1$	3	3	1	2	4
$^3P_0$	3	2	1	2	4
$^3P_1$	2	2	1	2	4
$^3P_2$	3	3	1	2	4
$^3P_2$-$^3F_2$	2	1	0	1	3
$^1D_2$	2	3	0	1	2
$^3D_1$	2	1	0	1	2
$^3D_2$	2	2	0	1	2
$^3D_3$	1	2	0	1	2
$^3D_3$-$^3G_3$	1	0	0	0	1
$^1F_3$	1	1	0	0	1
$^3F_2$	1	2	0	0	1
$^3F_3$	1	2	0	0	1
$^3F_4$	2	1	0	0	1
$^3F_4$-$^3H_4$	0	0	0	0	0
$^1G_4$	1	0	0	0	0
$^3G_3$	0	1	0	0	0
$^3G_4$	0	1	0	0	0
$^3G_5$	0	1	0	0	0
Total	35	38	9	24	50

Covariance Matrix

	C_S	C_A	C_V	C_{AV}	C_T
C_S	1.00	0.21	-0.93	-0.58	-0.39
C_A	0.23	1.00	-0.15	0.45	0.21
C_V	-0.93	-0.15	1.00	0.77	0.69
C_{AV}	-0.57	0.45	0.77	1.00	0.89
C_T	-0.39	0.21	0.69	0.89	1.00

as of July 8th, 2016

核力—微观核物理的基础

●维象传统核力

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LO Lagrangians

$$
\begin{aligned}
\mathcal{L}_{NN}^{(0)} &= C_S(\bar{\Psi}\Psi)(\bar{\Psi}\Psi) + C_A(\bar{\Psi}\gamma_5\Psi)(\bar{\Psi}\gamma_5\Psi) \\
&+ C_V(\bar{\Psi}\gamma_\mu\Psi)(\bar{\Psi}\gamma^\mu\Psi) + C_{AV}(\bar{\Psi}\gamma_\mu\gamma_5\Psi)(\bar{\Psi}\gamma^\mu\gamma_5\Psi) \\
&+ C_T(\bar{\Psi}\sigma_{\mu\nu}\Psi)(\bar{\Psi}\sigma^{\mu\nu}\Psi), \qquad (9)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{NN}} = {} & C_S^a\, \bar{\Psi}\tau^a\Psi\, \bar{\Psi}\tau^a\Psi + C_T^a\, \bar{\Psi}\tau^a\sigma_{\mu\nu}\Psi\, \bar{\Psi}\tau^a\sigma^{\mu\nu}\Psi \\
& + C_{AV}^a \bar{\Psi}\tau^a\gamma_5\gamma_\mu\Psi\, \bar{\Psi}\tau^a\gamma_5\gamma^\mu\Psi \\
& + C_V^a \bar{\Psi}\tau^a\gamma_\mu\Psi\, \bar{\Psi}\tau^a\gamma^\mu\Psi,
\end{aligned}
$$

indices, unless necessary, will be suppressed hereafter.) To have flavor singlets, the isospin structure of the two bilinears must be either $1 \otimes 1$ or $\tau^a \otimes \tau^a$. However, the latter needs not be considered, as it can be eliminated by Fierz rearrangement.