Antinucleon-nucleon interaction in chiral effective field theory

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Outline

Revival of Antinucleon-nucleon physics

- Near-threshold enhancement in the $\bar{p}p$ invariant-mass spectrum:
  $J/\psi \to \gamma\bar{p}p \quad \to$ BES collaboration (2003, 2012)
  $B^+ \to K^+\bar{p}p \quad \to$ BaBar collaboration (2005)
  $e^+e^- \to \bar{p}p \quad \to$ FENICE (1998), BaBar (2006, 2013)
  ($\bar{p}p \to e^+e^- \quad \to$ PS170 (1994))

  $\Rightarrow$ new resonances, $\bar{p}p$ bound states, exotic glueball states ?
- Facility for Antiproton and Ion Research (FAIR)
  - PANDA Project
    Study of the interactions between antiprotons and fixed target protons and nuclei in the momentum range of 1.5-15 GeV/c using the high energy storage ring HESR
  - PAX Collaboration
    experiments with a polarized antiproton beam
    transversity distribution of the valence quarks in the proton
    $\bar{N}N$ double-spin observables

$\bar{N}N$ partial-wave analysis

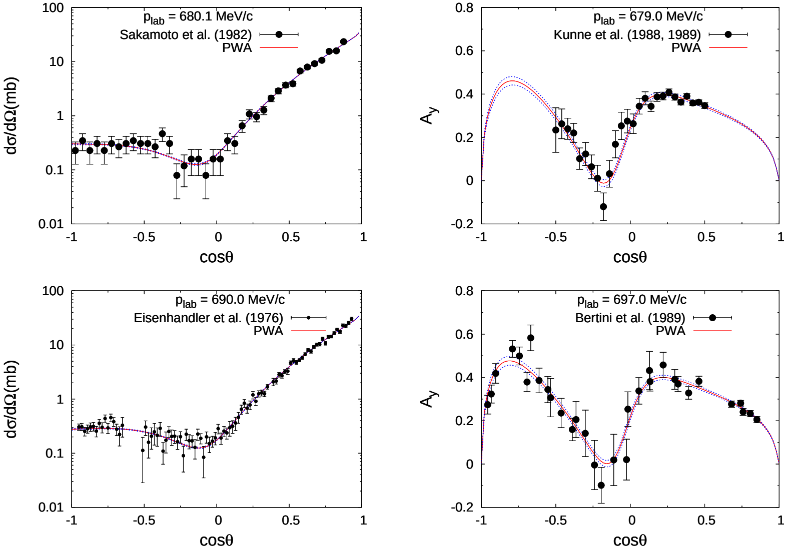
R. Timmermans et al., PRC 50 (1994) 48

- use a meson-exchange potential for the long-range part
- apply a strong absorption at short distances (boundary condition) in each individual partial wave ($\approx$ 1.2 fm)
- 30 parameters, fitted to a selection of $\bar{N}N$ data (3646!)
- However, resulting amplitudes are not explicitly given:
  no proper assessment of the uncertainties (statistical errors)
  phase-shift parameters for the $^1S_0$ and $^1P_1$ partial waves are not pinned down accurately

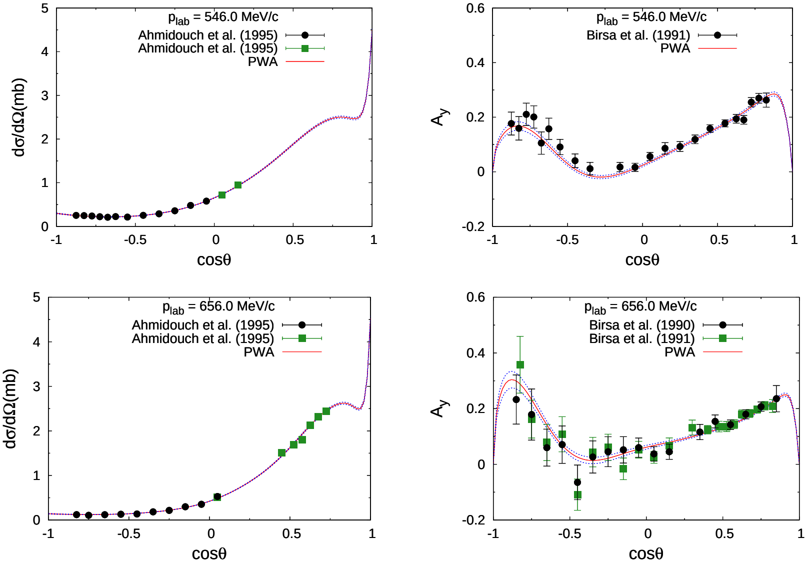
D. Zhou and R. Timmermans, PRC 86 (2012) 044003

- use now potential where the long-range part is fixed from chiral EFT (N^2LO)
- somewhat larger number of $\bar{N}N$ data (3749!)
- now, resulting amplitudes and phase shifts are given!
- lowest momentum: $p_{lab} = 100$ MeV/c ($T_{lab} = 5.3$ MeV)
- highest total angular momentum: $J = 4$

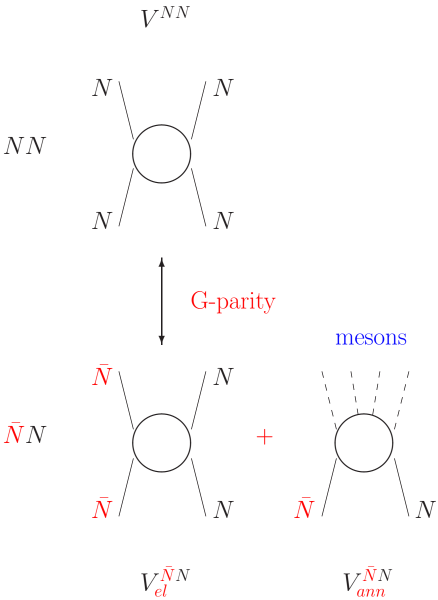
$\bar{N}N$ PWA: $\bar{p}p \to \bar{p}p$



$\bar{N}N$ PWA: $\bar{p}p \to \bar{n}n$



The $\bar{N}N$ interaction



Traditional approach: meson-exchange

I) $V^{\bar{N}N}_{el}$ ... derived from an *NN* potential via G-parity

(Charge conjugation plus 180^o rotation around the *y* axis in isospin space)

$\Rightarrow$

$$\begin{aligned} V^{\bar{N}N}(\pi,\ \omega) &= -V^{NN}(\pi,\ \omega) \ - \text{odd G} - \text{parity} \\ V^{\bar{N}N}(\sigma,\ \rho) &= +V^{NN}(\sigma,\ \rho) \ - \text{even G} - \text{parity} \\ &\ldots \end{aligned}$$

II) $V^{\bar{N}N}_{ann}$

employ a phenomenological optical potential, e.g.

$V_{opt}(r) = (U_0 + iW_0)\, e^{-r^2/(2a^2)}$

with parameters U_0, W_0, a fixed by a fit to $\bar{N}N$ data

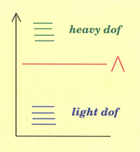
examples: Dover/Richard (1980,1982), Paris (1982,...,2009), Nijmegen (1984), Jülich (1991,1995), ...

Chiral Effective Field Theory

S. Weinberg, Physica 96A (1979) 327; PLB 251 (1990) 288

- Respect/exploit symmetries of the underlying QCD
- Different scales: Separation of low and high energy dynamics
  - low-energy dynamics is described in terms of the relevant degrees of freedom (e.g. pions)
  - high-energy dynamics remains unresolved

  $\rightarrow$ absorbed into contact terms



- Power counting

  Expand interaction in powers $Q^n = (q/\Lambda)^n$, $n = 0, 1, 2, ...$

  q ... soft scale (nucleon three-momentum, pion four-momentum, pion mass)

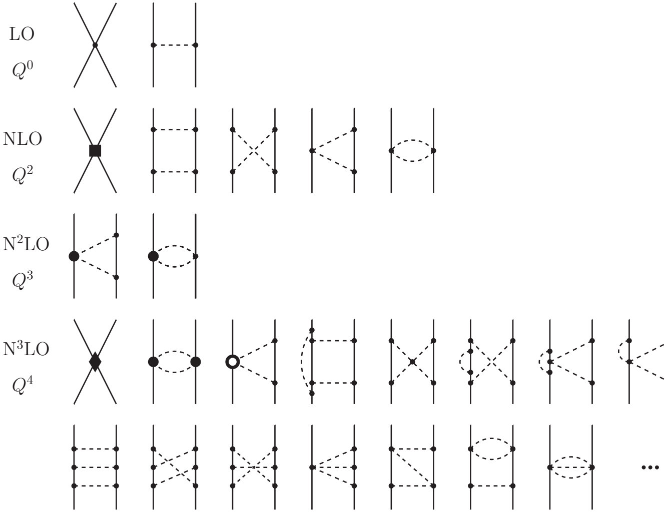
  Λ ... hard scale ($\approx$ 1 GeV ... m_ρ, M_N)

  $\Rightarrow$ systematic improvement of results by going to higher order (power)

  $\Rightarrow$ estimation of theoretical uncertainty

  expected to work for $q < \Lambda$

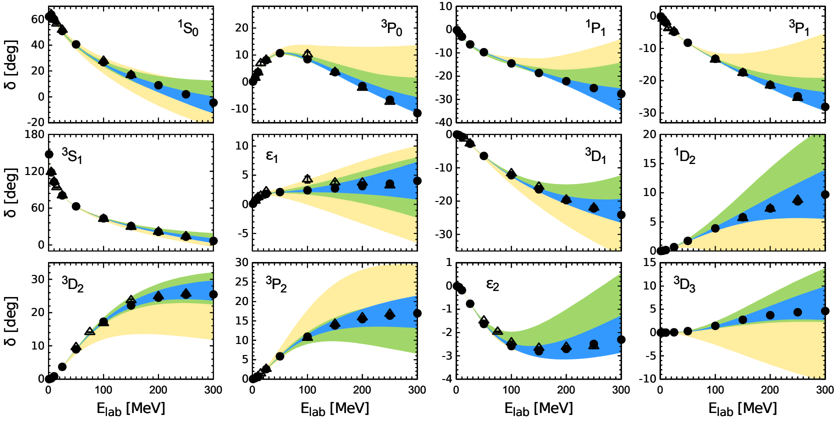
NN in chiral effective field theory



- 4*N* contact terms involve low-energy constants (LECs) ... parameterize unresolved short-range physics

⇒ need to be fixed by fit to experiments

NN in chiral effective field theory



E. Epelbaum, H. Krebs, Ulf-G. Meißner (EKM), EPJA 51 (2015) 53

—— LO, —— NLO, —— N^3LO

The $\bar{N}N$ interaction in chiral EFT

- $V^{NN} = \quad V_{1\pi} + V_{2\pi} + V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{el} = -V_{1\pi} + V_{2\pi} - V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{ann} = \sum_X V^{\bar{N}N\to X} \qquad X \hat{=} \pi, 2\pi, 3\pi, 4\pi, ...$

• $V_{1\pi}$, $V_{2\pi}$, ... can be taken over from a chiral EFT study of the *NN* interaction

⇒ starting point: "improved chiral *NN* potential up to N^{3}LO" by

Epelbaum, Krebs, Meißner, EPJA 51 (2015) 53

• V_{cont} has the same structure as in *NN*. However, the LECs have to be determined by a fit to $\bar{N}N$ data (phase shifts, inelasticites)!

no Pauli principle → more partial waves, more contact terms

• $V^{\bar{N}N}_{ann}$ has no counterpart in *NN*

• Ling-Yun Dai, JH, U.-G. Meißner, JHEP 07 (2017) 078 (N^{3}LO)
Xian-Wei Kang, JH, U.-G. Meißner, JHEP 02 (2014) 113 (N^{2}LO)

Annihilation potential

- experimental information:
  - annihilation occurs dominantly into 4 to 6 pions (two-body channels like $\bar{p}p \to \pi^+\pi^-$, $\rho^\pm\pi^\mp$ etc. contribute in the order of $\approx 1\%$)
  - thresholds: for 5 pions: $\approx$ 700 MeV   for $\bar{N}N$: 1878 MeV
  - produced pions have large momenta $\to$ annihilation process depends very little on energy
  - annihilation is a statistical process: properties of the individual particles (mass, quantum numbers) do not matter
- phenomenlogical models: bulk properties of annihilation can be described rather well by simple energy-independent optical potentials
- range associated with annihilation is around 1 fm or less
  $\to$ short-distance physics

$\Rightarrow$ describe annihilation in the same way as the short-distance physics in $V^{\bar{N}N}_{el}$, i.e. by contact terms (LECs)

$\Rightarrow$ describe annihilation by a few effective (two-body) annihilation channels (unitarity is preserved!)

$$V^{\bar{N}N} = V^{\bar{N}N}_{el} + V^{\bar{N}N}_{ann;eff}; \qquad V^{\bar{N}N}_{ann;eff} = \sum_X V^{\bar{N}N\to X} G^0_X V^{X\to\bar{N}N}$$

$$V^{\bar{N}N\to X}(p_{\bar{N}N}, p_X) \approx p^L_{\bar{N}N}\,(a + b\,p^2_{\bar{N}N} + ...); \quad p_X \approx \text{const.}$$

Contributions of V_{cont} for $\bar{N}N$ up to N^{3}LO

$V_{el}^{\bar{N}N}$

$$V^{L=0} = \tilde{C}_\alpha + C_\alpha (p^2 + p'^2) + D^1_\alpha p^2 p'^2 + D^2_\alpha (p^4 + p'^4)$$
$$V^{L=1} = C_\beta \, p \, p' + D_\beta \, p \, p' (p^2 + p'^2)$$
$$V^{L=2} = D_\gamma \, p^2 p'^2$$

$\tilde{C}_i$ ... LO LECs [4], C_i ... NLO LECs [+14], D_i ... N^{3}LO LECs [+30], $p = |\mathbf{p}|$; $p' = |\mathbf{p}'|$

$V_{ann;eff}^{\bar{N}N}$

$$V^{L=0}_{ann} = -i \, (\tilde{C}^a_\alpha + C^a_\alpha p^2 + D^a_\alpha p^4) \, (\tilde{C}^a_\alpha + C^a_\alpha p'^2 + D^a_\alpha p'^4)$$
$$V^{L=1}_{ann} = -i \, (C^a_\beta p + D^a_\beta p^3) \, (C^a_\beta p' + D^a_\beta p'^3)$$
$$V^{L=2}_{ann} = -i \, (D^a_\gamma)^2 p^2 p'^2$$
$$V^{L=3}_{ann} = -i \, (D^a_\delta)^2 p^3 p'^3$$

α ... $^1S_0$ and $^3S_1$
β ... $^3P_0$, $^1P_1$, and $^3P_1$
γ ... $^1D_2$, $^3D_2$ and $^3D_3$
δ ... $^1F_3$, $^3F_3$ and $^3F_4$

- unitarity condition: higher powers than what follows from Weinberg power counting appear!
- same number of contact terms (LECs)

regularized Lippmann-Schwinger equation

$$T^{L'L}(p',p) = V^{L'L}(p',p) + \sum_{L''} \int_0^\infty \frac{dp'' p''^2}{(2\pi)^3} \frac{V^{L'L''}(p',p'')\, T^{L''L}(p'',p)}{2E_p - 2E_{p''} + i\eta}$$

- employ the regularization scheme of EKM (EPJA 51 (2015) 53)

$\Rightarrow$ local regulator for pion exchange, nonlocal regulator for contact terms:

$$V_{n\pi}(q) \to V_{n\pi}(r) \times f_R(r) \to V^{reg}_{n\pi}(q); \qquad (\vec{q} = \vec{p}' - \vec{p})$$
$$V_{cont} = V(p,p') \to V(p,p') \times f_\Lambda(p,p') = V^{reg}_{cont}$$

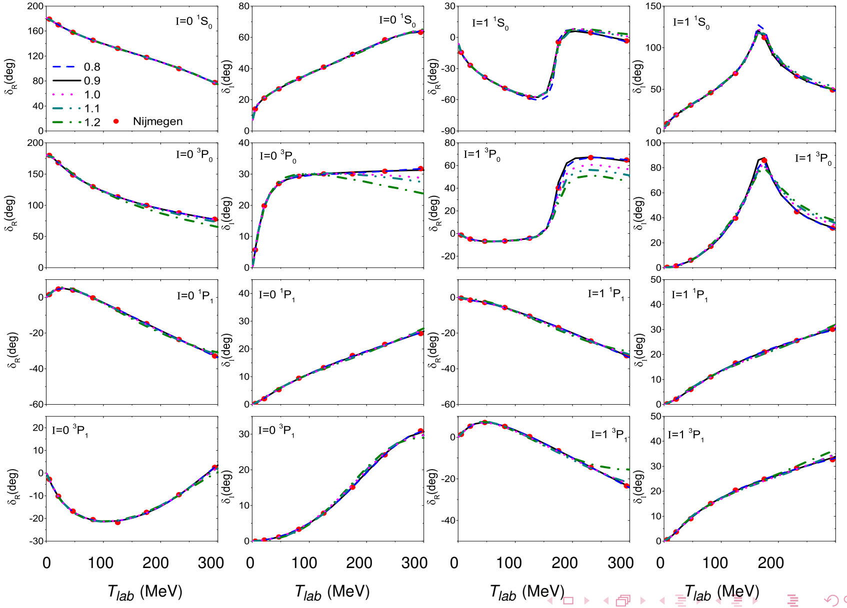
$(f_R(r) = \left[1 - exp(-r^2/R^2)\right]^6; \quad f_\Lambda(p,p') = exp(-(p^2 + p'^2)/\Lambda^2); \quad R = 0.8\text{-}1.2$ fm; $\Lambda = 2/R)$

- Fit to phase shifts and inelasticity parameters in the isospin basis

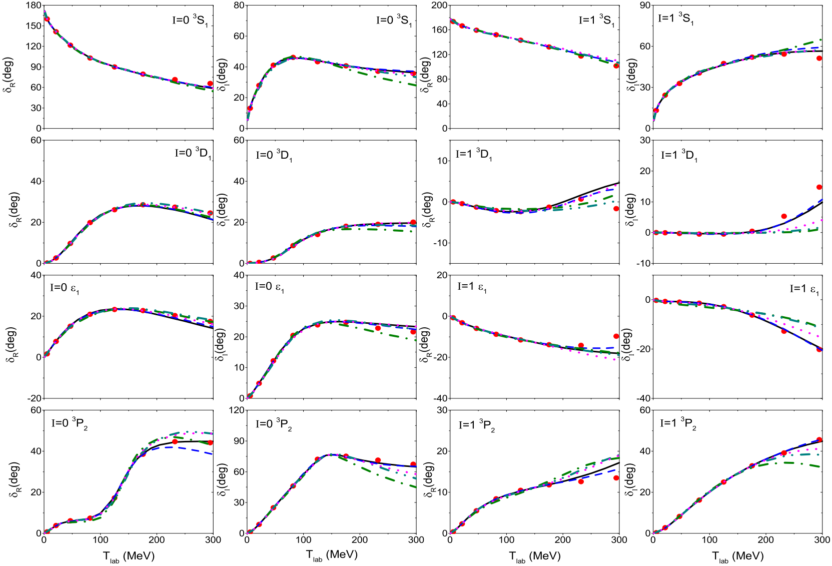
- Calculation of observables is done in particle basis:
  - $\star$ Coulomb interaction in the $\bar{p}p$ channel is included
  - $\star$ the physical masses of p and n are used

$\bar{n}n$ channels opens at $p_{lab} = 98.7$ MeV/c ($T_{lab} = 5.18$ MeV/c)

$\bar{N}N$ phase shifts (N^{3}LO)



$\bar{N}N$ phase shifts



Uncertainty

- Uncertainty for a given observable $X(p)$:
  (Epelbaum, Krebs, Meißner, EPJA 51 (2015) 53)
- estimate uncertainty via
  - the expected size of higher-order corrections
  - the actual size of higher-order corrections

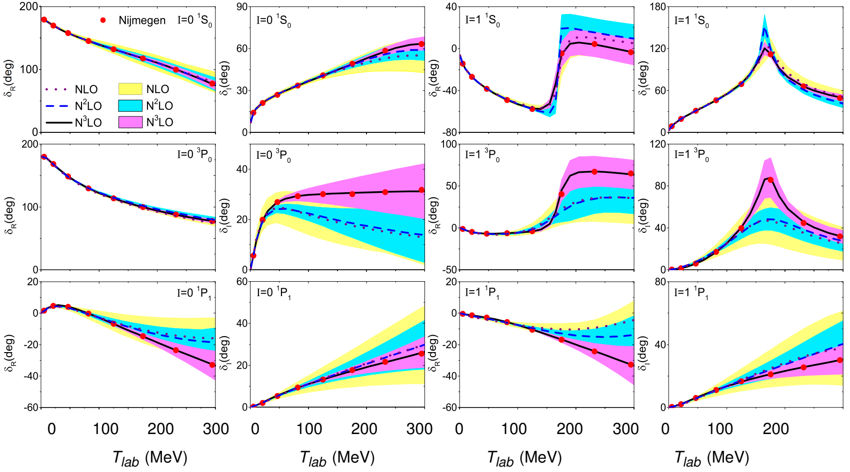
$$
\begin{aligned}
\Delta X^{LO} &= Q^2 |X^{LO}| \qquad (X^{NLO} \approx Q^2 X^{LO}) \\
\Delta X^{NLO} &= \max\left(Q^3 |X^{LO}|, Q^1 |\delta X^{NLO}|\right); \quad \delta X^{NLO} = X^{NLO} - X^{LO} \\
\Delta X^{N^2LO} &= \max\left(Q^4 |X^{LO}|, Q^2 |\delta X^{NLO}|, Q^1 |\delta X^{N^2LO}|\right); \quad \delta X^{N^2LO} = X^{N^2LO} - X^{NLO} \\
\Delta X^{N^3LO} &= \max\left(Q^5 |X^{LO}|, Q^3 |\delta X^{NLO}|, Q^2 |\delta X^{N^2LO}|, Q^1 |\delta X^{N^3LO}|\right); \quad \delta X^{N^3LO} = X^{N^3LO} - X^{N^2LO}
\end{aligned}
$$

- expansion parameter Q is defined by

$$Q = \max\left(\frac{p}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right); \qquad p \ldots \bar{N}N \text{ on} - \text{shell momentum}$$

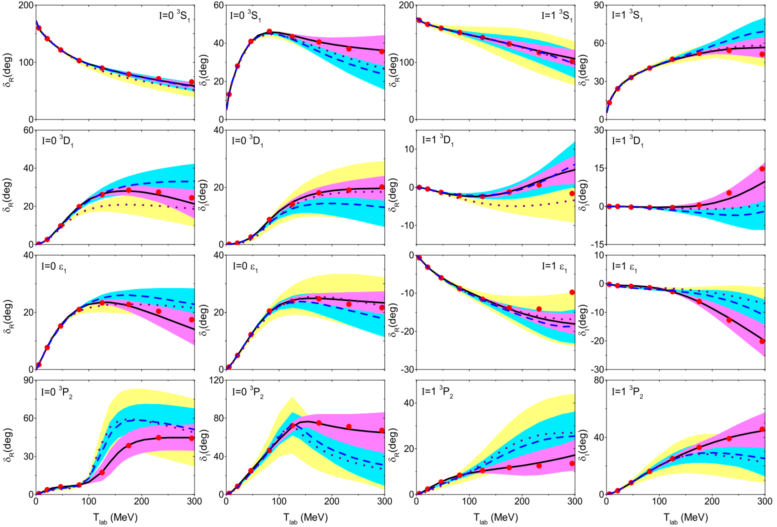
Λ_b ... breakdown scale $\rightarrow \Lambda_b = 500 - 600$ MeV [for $R = 0.8 - 1.2$ fm] (EKM, 2015)

$\bar{N}N$ phase shifts



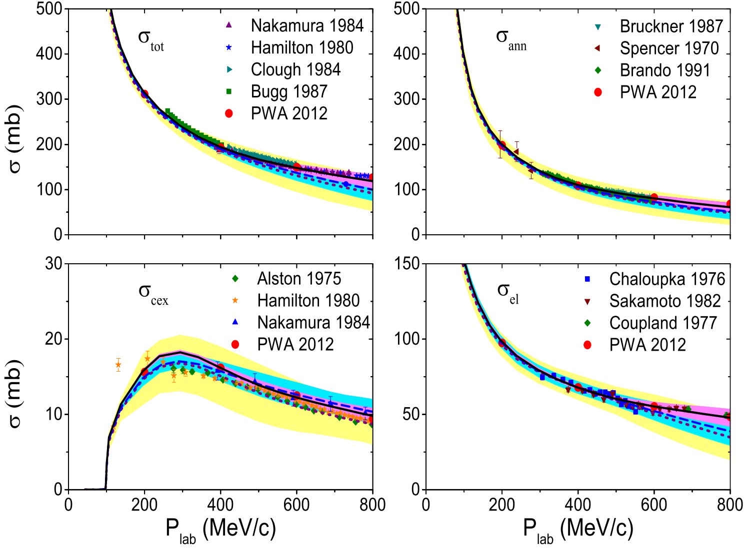
N³LO; N²LO; NLO (cutoff $R = 0.9$ fm)

$\bar{N}N$ phase shifts



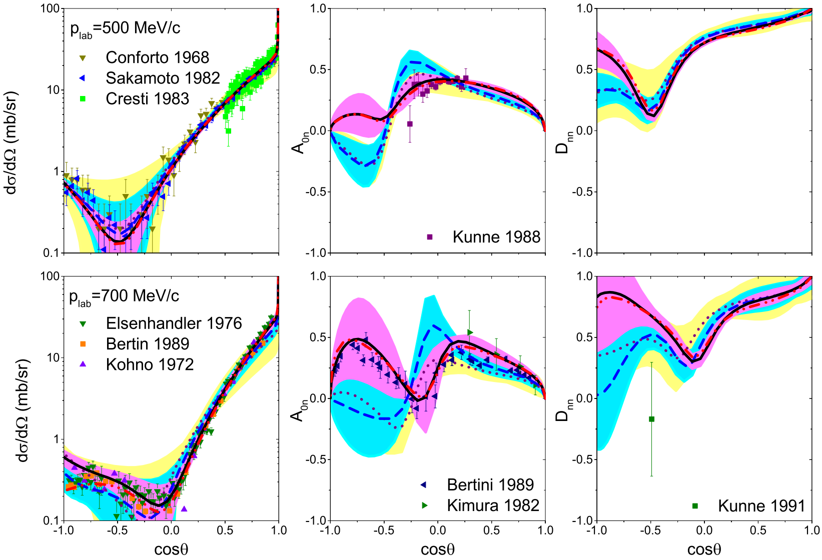
further results: Ling-Yun Dai, JH, U.-G. Meißner, JHEP 07 (2017) 078

$\bar{p}p$ integrated cross sections



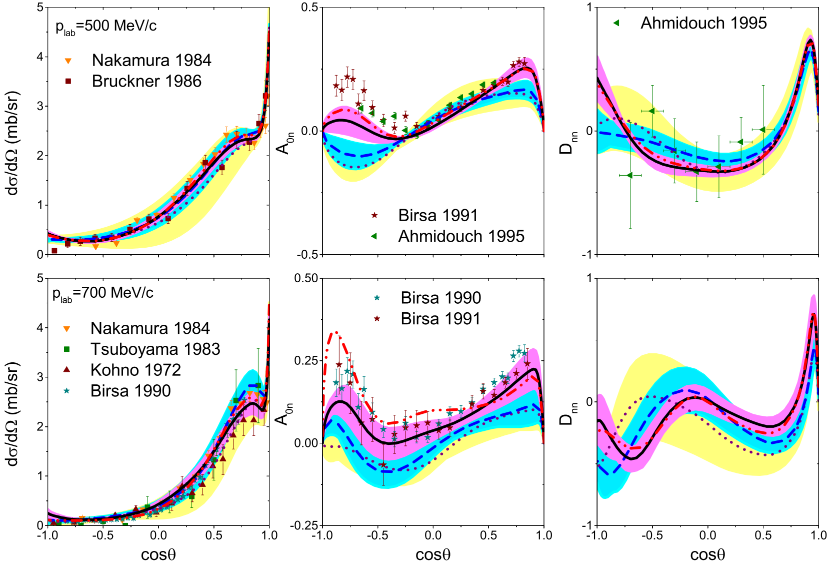
N^{3}LO; N^{2}LO; NLO

$\bar{p}p \to \bar{p}p$



PWA; N^{3}LO; N^{2}LO; NLO (T_{lab} = 125 MeV, 232 MeV)

$\bar{p}p \rightarrow \bar{n}n$



Hadronic level shifts in hyperfine states of $\bar{p}H$

Deser-Trueman formula:

$$\Delta E_S + \mathrm{i}\,\frac{\Gamma_S}{2} = -\frac{4}{M_p r_B^3} a_S^{sc} \left(1 - \frac{a_S^{sc}}{r_B}\beta\right)$$
$$\Delta E_P + \mathrm{i}\,\frac{\Gamma_P}{2} = -\frac{3}{8 M_p r_B^5} a_P^{sc}$$

r_B ... Bohr radius ... 57.6 fm; $\beta = 2(1-\Psi(1)) \approx 3.1544$
a^{sc} ... Coulomb-distorted $\bar{p}p$ scattering length

Carbonell, Richard, Wycech, ZPA 343 (1992) 343:
works well once Coulomb and p-n mass difference is taken into account

NOTE:

different sign conventions for scattering lengths in $\bar{N}N$ and $\bar{K}N$!

$\Delta E < 0 \Leftrightarrow$ repulsive shift

Hadronic level shifts in hyperfine states of $\bar{p}H$

	NLO	N^2LO	N^3LO	N^2LO*	Experiment
$E_{^1S_0}$ (eV)	−448	−446	−443	−436	−440(75) [1]
					−740(150) [2]
$\Gamma_{^1S_0}$ (eV)	1155	1183	1171	1174	1200(250) [1]
					1600(400) [2]
$E_{^3S_1}$ (eV)	−742	−766	−770	−756	−785(35) [1]
					−850(42) [3]
$\Gamma_{^3S_1}$ (eV)	1106	1136	1161	1120	940(80) [1]
					770(150) [3]
$E_{^3P_0}$ (meV)	17	12	8	16	139(28) [4]
$\Gamma_{^3P_0}$ (meV)	194	195	188	169	120(25) [4]
E_{1S} (eV)	−670	−688	−690	−676	−721(14) [1]
Γ_{1S} (eV)	1118	1148	1164	1134	1097(42) [1]
E_{2P} (meV)	1.3	2.8	4.7	2.3	15(20) [4]
Γ_{2P} (meV)	36.2	37.4	37.9	27	38.0(2.8) [4]

[1] Augsburger et al., NPA 658 (1999) 149; [2] Ziegler et al., PLB 206 (1988) 151;
[3] Heitlinger et al., ZPA 342 (1992) 359; [4] Gotta et al., NPA 660 (1999) 283

* Xian-Wei Kang et al., JHEP 02 (2014) 113

Evidence for $\bar{N}N$ bound states?

E_B, M_R (MeV)	N^2LO [1]	El-Bennich [2]	Entem [3]	Milstein [4]
$^{11}S_0$	-	-4.8-i 26	-	22-i 33
$^{31}S_0$	-37-i 47*	-	-	-
$^{13}S_1$	$+(5.6 \cdots 7.7) - \mathrm{i}\,(49.2 \cdots 60.5)$	-	-	-
$^{11}P_1$	-	1877±i 13	-	-
$^{13}P_0$	$-(3.7 \cdots 0.2) - \mathrm{i}\,(22.0 \cdots 26.4)$	1876±i 5	1895±i 17	-
$^{33}P_0$	-	1871±i 11	-	-
$^{13}P_1$	-	1872±i 10	-	-
$^{33}P_1$	-	-4.5-i 9	-	-

Notation: $^{(2I+1)(2S+1)}L_J$ $\qquad M_p + M_{\bar{p}} = 1876.574$ MeV

[1] Xian-Wei Kang et al., JHEP 02 (2014) 113; * needed for $J/\psi \to \gamma\bar{p}p$
[2] B. El-Bennich et al., PRC 79 (2009) 054001
[3] D.R. Entem & F. Fernández, PRC 73 (2006) 045214
[4] A.I. Milstein & S.G. Salnikov, NPA 966 (2017) 54

BES 2005; BESIII 2011,2016: $X(1835)$ $\quad (J^{PC} = 0^{-+}, I = 0)$

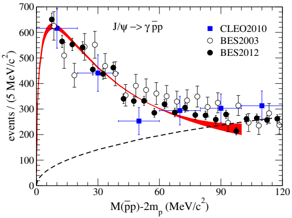
seen in $J/\psi \to \gamma\pi^+\pi^-\eta'$: $M_R = 1836.5 \pm 3^{+5.6}_{-2.1}$ MeV, $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV

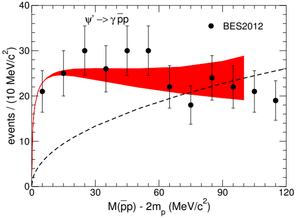
evidence (?) in $J/\psi \to \gamma\bar{p}p$: $M_R = 1832^{+19}_{-5}{}^{+18}_{-17}$ MeV, $\Gamma < 76$ MeV (90 % C.L.)

$\bar{p}p$ in final state

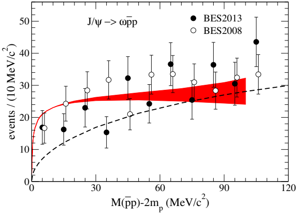
X.-W. Kang, JH, U.-G. Meißner, PRD 91 (2015) 074003 (N^{2}LO)

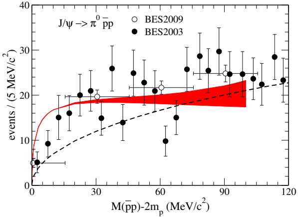
bands represent cutoff variations!





$J/\psi \to \gamma\bar{p}p$ (left)
$\psi' \to \gamma\bar{p}p$ (right)





$J/\psi \to \omega\bar{p}p$ (left)
$J/\psi \to \pi^0\bar{p}p$ (right)

Summary & Outlook

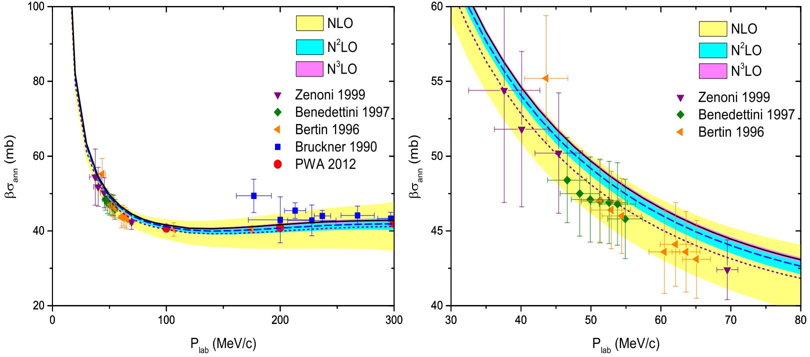
- $\bar{N}N$ interaction at N^{3}LO in chiral effective field theory
- new local regularization scheme is used for pion-exchange contributions
- new uncertainty estimate suggested by Epelbaum, Krebs, Meißner

- excellent description of $\bar{N}N$ amplitudes is achieved
- nice agreement with $\bar{p}p$ observables for $T_{lab} \leq 250$ MeV is achieved
- predictions are made for low energies ($T_{lab} \leq 5.3$ MeV):
  - low-energy annihilation cross section
  - level shifts of antiprotonic atoms

$\Rightarrow$ approach works not only for NN but also rather well for $\bar{N}N$

- try our own PWA
- analyze $\bar{p}p \to \pi\pi$, $\bar{K}K$ channels
- consider $\bar{p}d$ scattering
- new data $\bar{N}N$ data?

$\bar{p}p$ annihilation cross section



$$\beta = \frac{v_{\bar{p}}}{c}$$

- anomalous threshold behavior due to attractive Coulomb interaction

$\bar{n}p$ cross sections