Antinucleon-nucleon interaction

in chiral effective field theory

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Outline

$\bar{p}p$ scattering measurements at LEAR

Measurement	Incoming $\bar{p}$ momentum (MeV/c)	Experiment
integrated cross sections		
$\sigma_{tot}(\bar{p}p)$	222-599 (74 momenta)	PS172
	181,219,239,261,287,505,590	PS173
$\sigma_{ann}(\bar{p}p)$	177-588 (53 momenta)	PS173
	38-174 (14 momenta)	PS201
$\bar{p}p$ elastic scattering		
ρ = Re $f(0)$/Im $f(0)$	233,272,550,757,1077	PS172
	181,219,239,261,287,505,590	PS173
$d\sigma/d\Omega$	679-1550 (13 momenta)	PS172
	181,287,505,590	PS173
	439,544,697	PS198
A_{0n}	497-1550 (15 momenta)	PS172
	439,544,697	PS173
D_{0n0n}	679-1501 (10 momenta)	PS172
$\bar{p}p$ charge exchange		
$d\sigma/d\Omega$	181-595 (several momenta)	PS173
	546,656,693,767,875,1083,1186,1287	PS199
	601.5,1202	PS206
A_{0n}	546,656,767,875,979,1083,1186,1287	PS199
D_{0n0n}	546,875	PS199
K_{n00n}	875	PS199

Post-LEAR era

- Search for glueballs:
  $\bar{p}p \to \pi\pi\pi$, $\bar{p}p \to \pi\pi\eta$, $\bar{p}p \to \pi\eta\eta$
  (Asterix collaboration, Crystal Barrel collaboration)
- Near-threshold enhancement in the $\bar{p}p$ invariant-mass spectrum:
  $J/\psi \to \gamma\bar{p}p \quad \to$ BES collaboration (2003)
  $B^+ \to K^+\bar{p}p \quad \to$ BaBar collaboration (2005)
  $e^+e^- \to \bar{p}p \quad \to$ PS170 (1994), FENICE (1998), BaBar (2006)
- 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:
  "It does not make much sense to present all these phase shifts, inelasticities and mixing parameters without a proper assessment of the uncertainties (statistical errors). This, however, requires a lot of work. Preliminary study shows that the phase-shift parameters for the $^1S_0$ and $^1P_1$ partial waves are not pinned down accurately at all above $p_{\rm lab} \approx 400$ MeV/c."

Criticisms (J.-M. Richard, PRC 52 (1995) 1143)

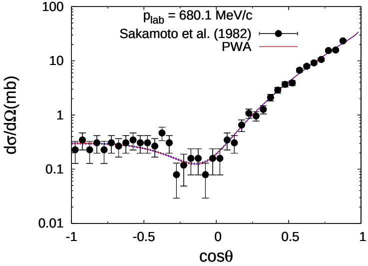
- data pruning
  some $\bar{N}N$ scattering data are clearly incompatible
  but which are right and which are wrong?
- Prejudice in favor of pre-LEAR (pre 1980) data
- uniqueness of solution
  no Pauli principle, phase shifts are complex: 4 $\times$ more PW's than in NN!
  few polarization data, practically no double- or triple-scattering experiments

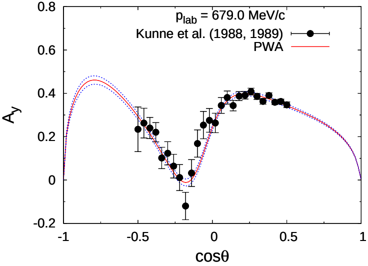
$\bar{N}N$ partial-wave analysis (updated!)

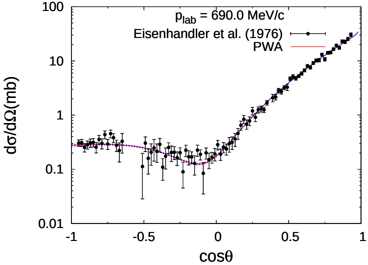
D. Zhou and R. Timmermans, PRC 86 (2012) 044003

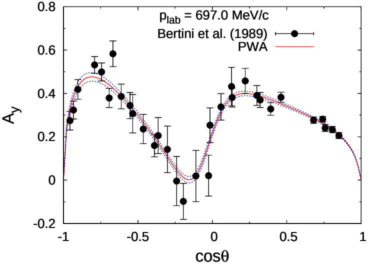
- use now potential where the long-range part is fixed from chiral EFT (N^2LO)
- somewhat larger number of $\bar{N}N$ data (3749!)
- none the less, same criticisms as before can be raised!
- now, resulting amplitudes and phase shifts are given!
- lowest momentum: $p_{lab} = 100$ MeV/c ($T_{lab} = 5.3$ MeV)
- highest total angular momentum: $J = 4$

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

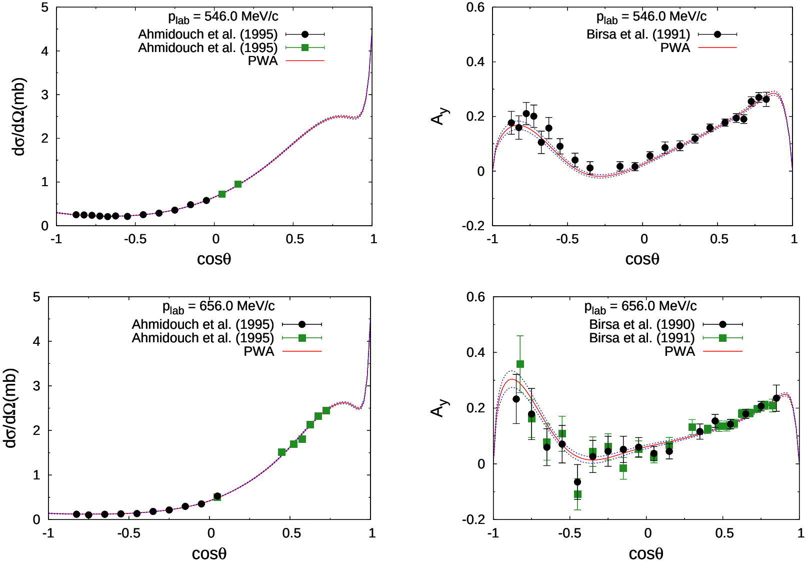




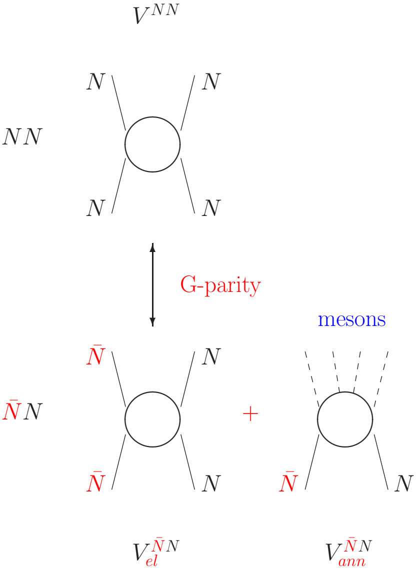




$\bar{N}N$ PWA $\bar{p}p \to \bar{n}n$



The $\bar{N}N$ interaction



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

- $V^{NN} = \quad V_{1\pi} + V_{2\pi} + V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{el} = -V_{1\pi} + V_{2\pi} - V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{ann} = \sum_X V^{\bar{N}N \to X}$
  X ... open annihilation channels (π, 2π, 3π, 4π, ...)

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

⇒ take the new "improved chiral *NN* potential up to N^3LO" by
Epelbaum, Krebs, Meißner [EPJA 51 (2015) 53]
as starting point

⇒ adopt the same regularization scheme:
local regulator for pion exchange, nonlocal regulator for contact terms

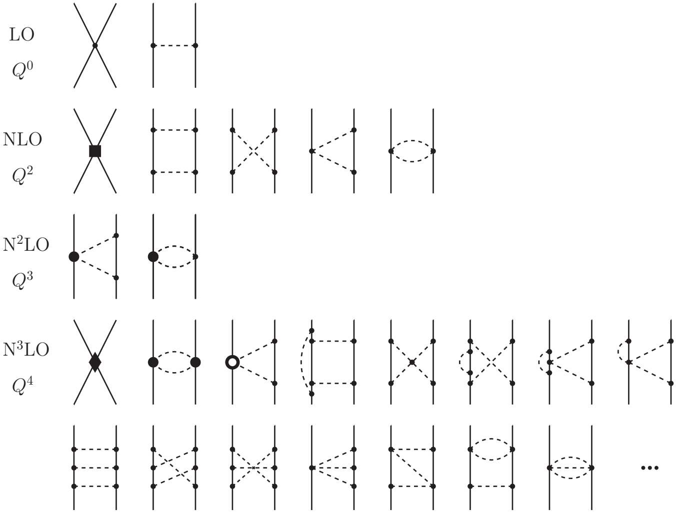
$$\left(f_R(r) = \left[1 - exp(-r^2/R^2)\right]^6; \quad f_\Lambda(p,p') = exp(-(p^2 + p'^2)/\Lambda^2); \quad \Lambda = 2/R\right)$$

- 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)!

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

- Xian-Wei Kang et al., JHEP 1402 (2014) 113 (N^2LO)
- Ling-Yun Dai et al., *arXiv:1702.02065* (N^3LO)

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



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 $V_{el}^{\bar{N}N}$, i.e. by contact terms

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

$$V^{\bar{N}N} = V_{el}^{\bar{N}N} + V_{ann;eff}^{\bar{N}N}; \qquad V_{ann;eff}^{\bar{N}N} = \sum_X V^{\bar{N}N\to X} G_X^0 V^{X\to\bar{N}N}$$

$$V^{\bar{N}N\to X}(p_{\bar{N}N}, p_X) \approx p_{\bar{N}N}^L (a + b\, p_{\bar{N}N}^2 + ...)$$

Annihilation potential

$$
\begin{aligned}
V_{ann}^{L=0} &= -i\,(\tilde{C}^a_{^1S_0} + C^a_{^1S_0}p^2 + D^a_{^1S_0}p^4)\,(\tilde{C}^a_{^1S_0} + C^a_{^1S_0}p'^2 + D^a_{^1S_0}p'^4) \\
V_{ann}^{L=1} &= -i\,(C^a_\alpha p + D^a_\alpha p^3)\,(C^a_\alpha p' + D^a_\alpha p'^3) \\
V_{ann}^{L=2} &= -i\,(D^a_\beta)^2 p^2 p'^2 \\
V_{ann}^{L=3} &= -i\,(D^a_\gamma)^2 p^3 p'^3
\end{aligned}
$$

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

$$
\begin{aligned}
V_{ann}^{S\to S} &= -i\,(\tilde{C}^a_{^3S_1} + C^a_{^3S_1}p^2 + D^a_{^3S_1}p^4)\,(\tilde{C}^a_{^3S_1} + C^a_{^3S_1}p'^2 + D^a_{^3S_1}p'^4) \\
V_{ann}^{S\to D} &= -i\,(\tilde{C}^a_{^3S_1} + C^a_{^3S_1}p^2 D^a_{^3S_1}p^4)\; C^a_{\epsilon_1}p'^2 \\
V_{ann}^{D\to S} &= -i\,C^a_{\epsilon_1}p^2\,(\tilde{C}^a_{^3S_1} + C^a_{^3S_1}p'^2 + D^a_{^3S_1}p'^4) \\
V_{ann}^{D\to D} &= -i\,[(C^a_{\epsilon_1})^2 + (C^a_{^3D_1})^2]p^2p'^2
\end{aligned}
$$

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

effective χ square

Fit to phase shifts and inelasticity parameters in the isospin basis

$\tilde{\chi}^2 \approx |S_{LL'} - S_{LL'}^{PWA}|^2/\Delta^2$ ... $S_{LL'}$ are S-matrix elements

(no uncertainties for the PWA given $\rightarrow$ Δ^2 ... simple scaling parameter)

	R=0.8 fm	R=0.9 fm	R=1.0 fm	R=1.1 fm	R=1.2 fm
$T_{lab} \leq 25$ MeV	0.003	0.004	0.004	0.019	0.036
$T_{lab} \leq 100$ MeV	0.023	0.025	0.036	0.090	0.176
$T_{lab} \leq 200$ MeV	0.106	0.115	0.177	0.312	0.626
$T_{lab} \leq 300$ MeV	2.012	2.171	3.383	5.531	9.479

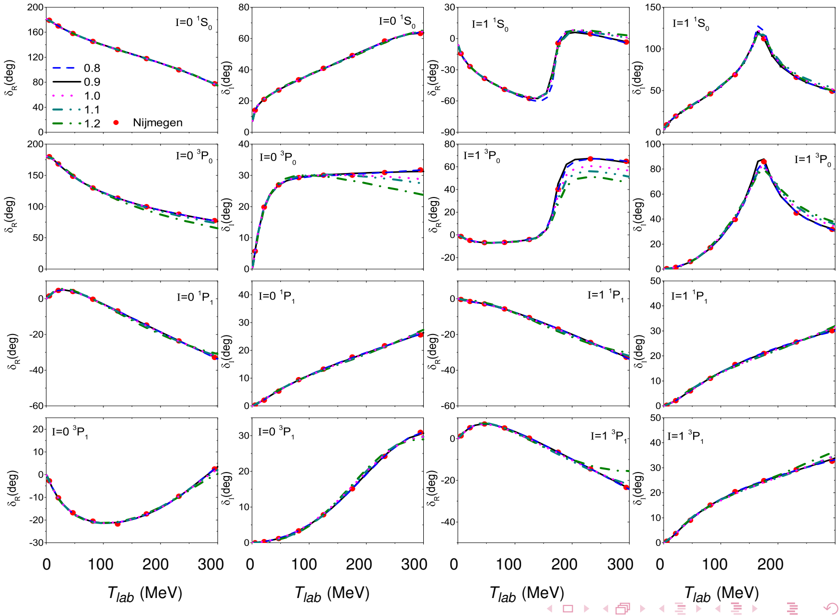
- minimum around $R = 0.8 \sim 0.9$ fm ($R = 0.9 \sim 1.0$ fm in the NN case)

Calculation of observables is done in particle basis:

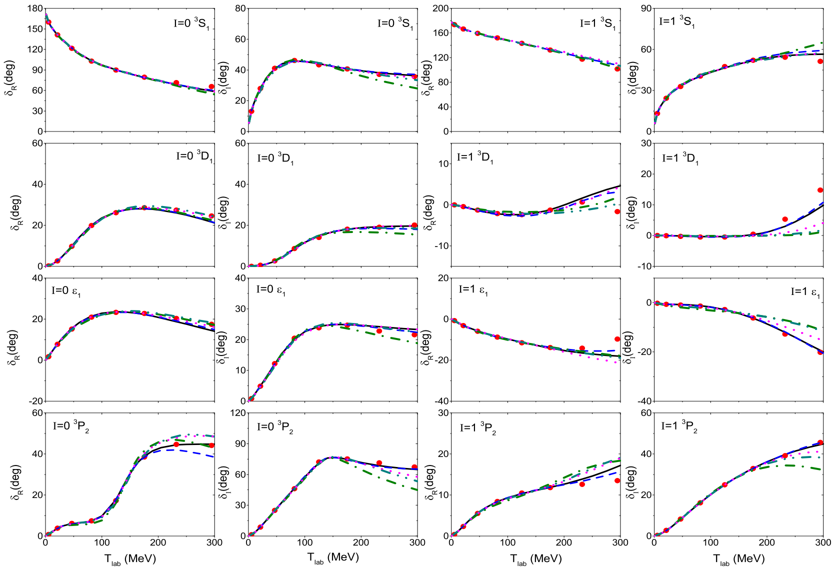
- Coulomb interaction in the $\bar{p}p$ channel is included
- the physical masses of p and n are used

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

$\bar{N}N$ phase shifts



$\bar{N}N$ phase shifts



Residual cutoff dependence

- Assessment of the residual cutoff dependence:
  (H. W. Grießhammer, *PoS CD* 15 (2016) 104)

  $|1 - \cot \delta^{(R_1)}(k) / \cot \delta^{(R_2)}(k)|$

  R_1 and R_2 ... two different values of the cutoff radius
  k ... on-shell momentum

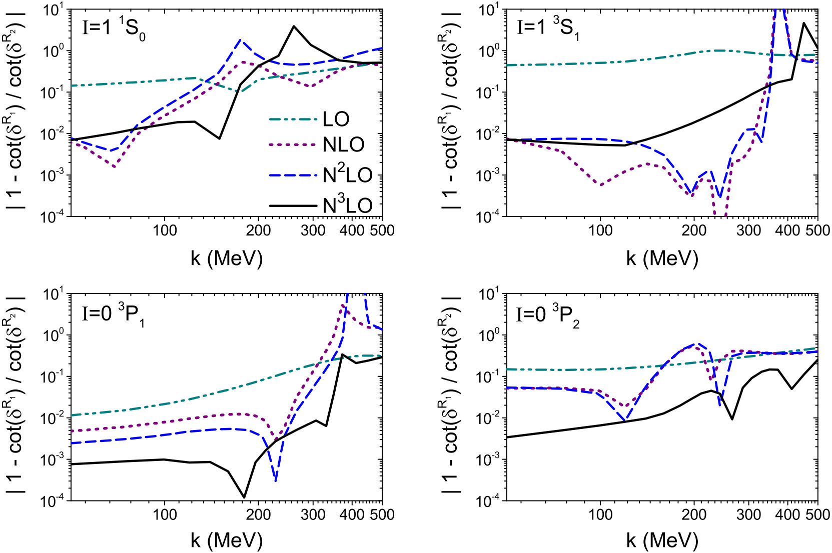
- Residual cutoff dependence:
  provides estimation of effects of higher-order contact interactions beyond the truncation level

  $\Rightarrow$ reduction of residual cutoff dependence for

  - LO $\rightarrow$ NLO/N^{2}LO
  - NLO/N^{2}LO $\rightarrow$ N^{3}LO/N^{4}LO

  (i.e. whenever additional contact terms arise)

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



Uncertainty

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

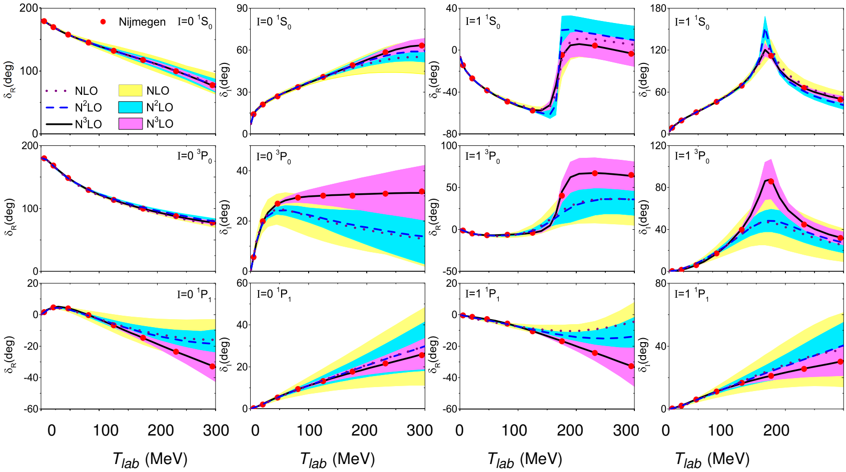
$$
\begin{aligned}
\Delta X^{LO} &= Q^2 |X^{LO}| \\
\Delta X^{NLO} &= \max\left(Q^3 |X^{LO}|,\, Q^1 |\delta X^{NLO}|\right); \quad \delta X^{NLO} = X^{NLO} - X^{LO} \\
\Delta X^{N^2LO} &= \max\left(Q^4 |X^{LO}|,\, Q^2 |\delta X^{NLO}|,\, Q^1 |\delta X^{N^2LO}|\right); \quad \delta X^{N^2LO} = X^{N^2LO}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

- expansion parameter Q is defined by

$$Q = \max\left(\frac{k}{\Lambda_b},\ \frac{M_\pi}{\Lambda_b}\right)$$

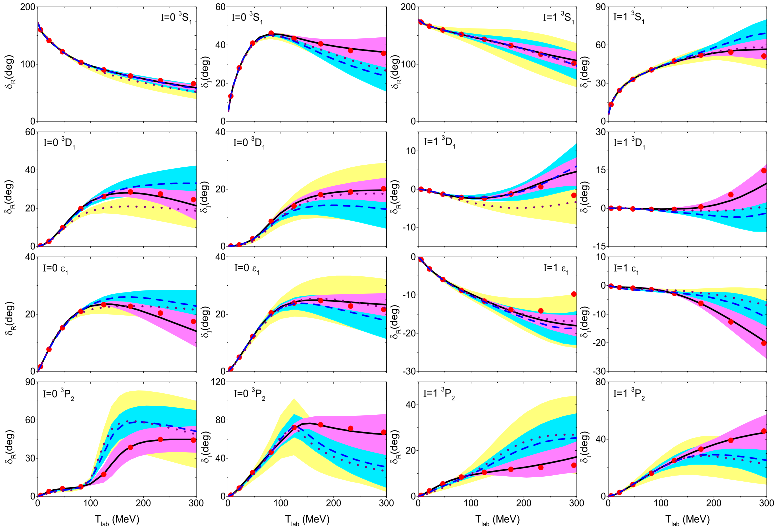
Λ_b ... breakdown scale $\rightarrow \Lambda_b = 500 - 600$ MeV [for $R = 0.8 - 1.2$ fm] (EKM, 2015)

$\bar{N}N$ phase shifts

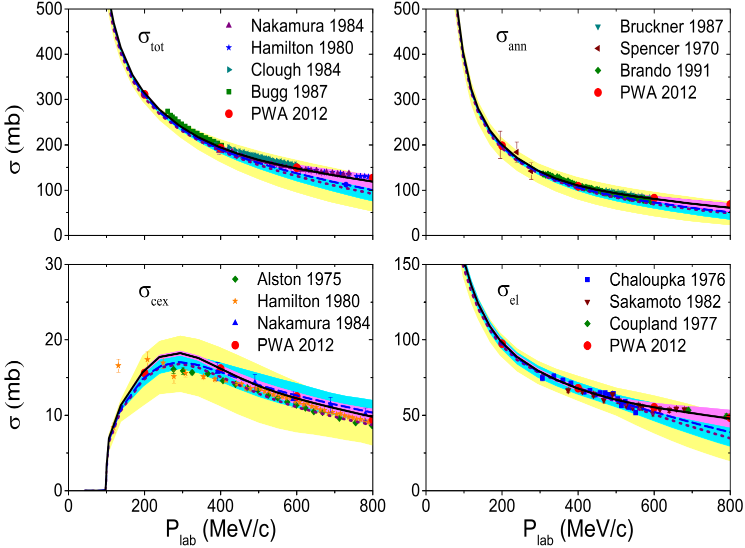


N3LO; N2LO; NLO

$\bar{N}N$ phase shifts



$\bar{p}p$ integrated cross sections



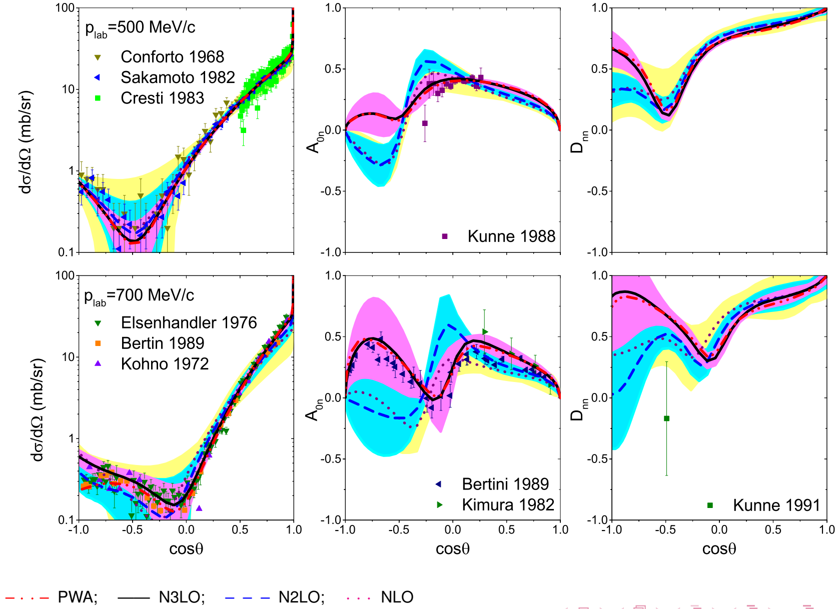
N3LO; N2LO; NLO

$\bar{N}N$ partial-wave cross sections

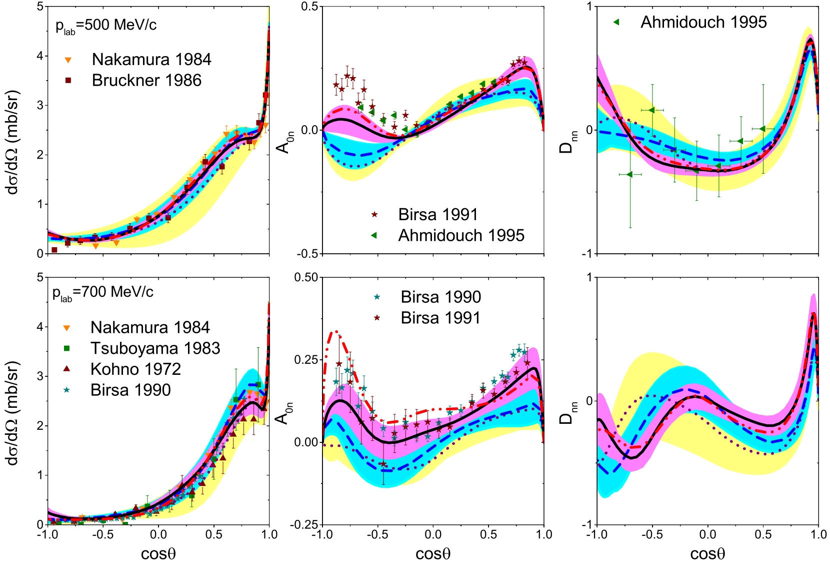
	p_{lab} (MeV/c)	$\bar{p}p \to \bar{p}p$ 200	400	600	800	$\bar{p}p \to \bar{n}n$ 200	400	600	800
$^1S_0$	N^{3}LO	15.9	8.0	4.1	2.0	0.7	0.1		
	PWA	15.7	7.9	4.1	2.1	0.7	0.1		
$^3S_1$	N^{3}LO	66.6	25.9	13.1	8.0	2.9	0.9	0.5	0.3
	PWA	66.1	26.0	13.2	8.8	3.0	1.0	0.5	0.2
$^3P_0$	N^{3}LO	4.9	5.4	5.1	3.6	1.5	0.8	0.1	
	PWA	4.9	5.4	5.0	3.5	1.5	0.8	0.1	
$^1P_1$	N^{3}LO	1.0	2.5	4.4	5.6	0.8	0.1		
	PWA	0.9	2.5	4.5	5.6	0.8	0.1		
$^3P_1$	N^{3}LO	1.8	5.0	4.1	3.6	5.1	3.0	0.2	0.1
	PWA	1.8	4.9	4.0	3.5	4.9	2.9	0.2	0.1
$^3P_2$	N^{3}LO	7.0	17.1	14.1	9.9	1.0	1.5	0.4	0.1
	PWA	7.0	17.0	13.9	9.6	0.9	1.4	0.4	0.1

(N^{3}LO with $R = 0.9$ fm)

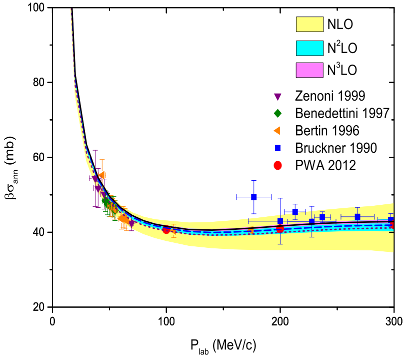
$\bar{p}p \rightarrow \bar{p}p$

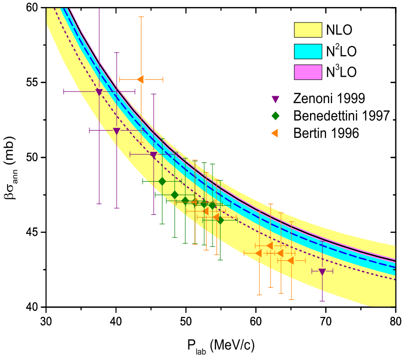


$\bar{p}p \to \bar{n}n$



$\bar{p}p$ annihilation cross section

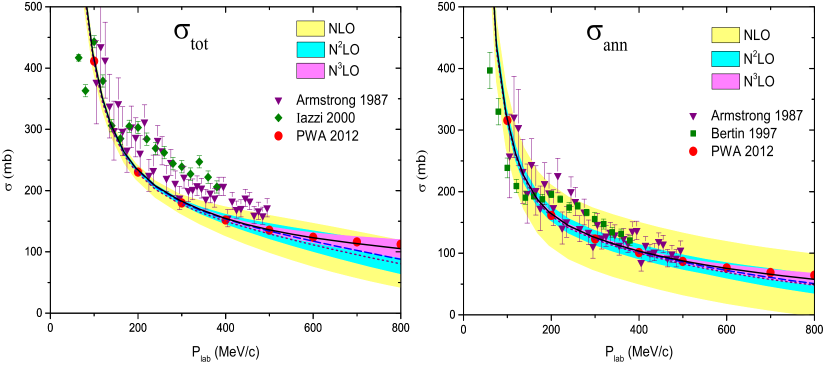




$$\beta = \frac{v_{\bar{p}}}{c}$$

- anomalous threshold behavior due to attractive Coulomb interaction

$\bar{n}p$ cross sections



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

Deser-Truman 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; $\beta = 2(1 - \Psi(1)) \approx 3.1544$

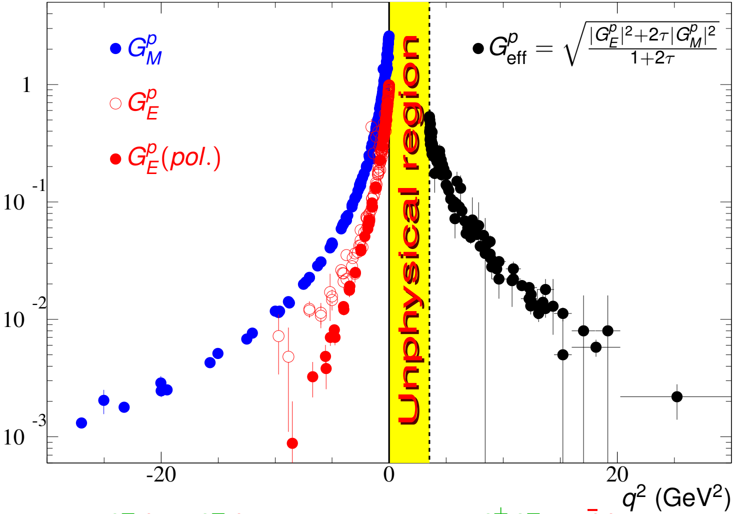
Hadronic level shifts in hyperfine states of $\bar{p}H$

	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 1999; [2] Ziegler 1988; [3] Heitlinger 1988; [4] Gotta 1999

* X.W. Kang et al., JHEP 1402 (2014) 113

Electromagnetic form factors of the proton



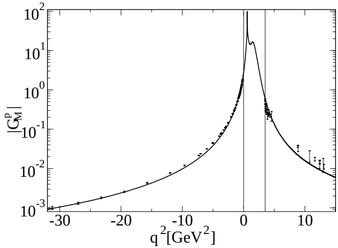
$e^- p \to e^- p$

space-like

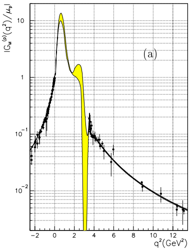
$e^+ e^- \leftrightarrow \bar{p} p$

time-like

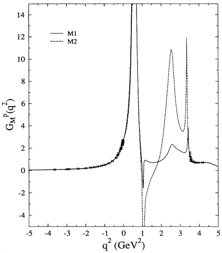
what happens in the unphysical region?



Faessler et al. 2010

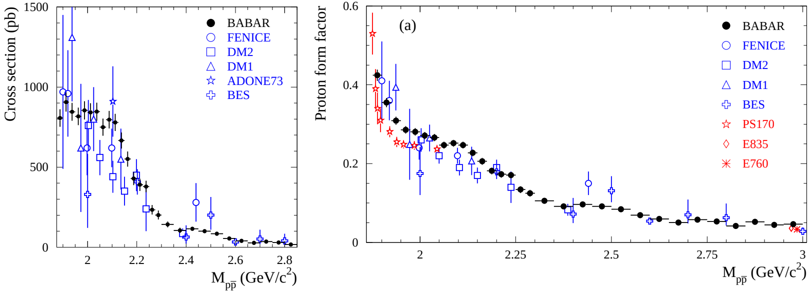


Baldini et al. 1999



Williams/Krewald 1995

Time-like region: $e^+e^- \to \bar{p}p$



$$\sigma_{e^+e^- \to \bar{p}p} = \frac{4\pi\alpha^2\beta}{3s}\, C_p(s) \left[|G_M(s)|^2 + \frac{2M_p^2}{s} |G_E(s)|^2 \right]$$

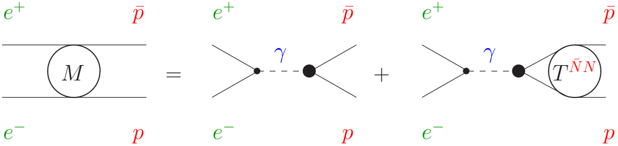
$$|G_{\rm eff}(s)| = \sqrt{\frac{\sigma_{e^+e^- \to \bar{p}p}(s)}{\frac{4\pi\alpha^2\beta}{3s}\, C_p(s) \left[1 + \frac{2M_p^2}{s}\right]}}$$

$\sqrt{s} = M_{\bar{p}p}$, $\beta = k_p/k_e \approx 2\,k_p/\sqrt{s}$, $C_p(s)$ ... Sommerfeld-Gamov factor

BABAR: J.P. Lees et al., PRD 87 (2013) 092005

Calculate $e^+e^- \to \bar{p}p$ in DWBA

one-photon exchange $\Rightarrow$ $\bar{N}N$, e^+e^- are in the $^3S_1$, $^3D_1$ partial waves



$$M_{L,L'} \propto f_L^{e^+e^-} \cdot f_{L'}^{\bar{p}p}$$

$$f_{L=0}^{e^+e^-} = \left[1 + \frac{m_e}{\sqrt{s}}\right]; \quad f_{L=2}^{e^+e^-} = \left[1 - \frac{2m_e}{\sqrt{s}}\right]$$

$$f_{L=0}^{\bar{p}p} = \left[G_M + \frac{M_p}{\sqrt{s}} G_E\right]; \quad f_{L=2}^{\bar{p}p} = \left[G_M - \frac{2M_p}{\sqrt{s}} G_E\right]$$

$$f_{L=2}^{\bar{p}p}(k_p = 0) = 0 \ \rightarrow \ G_M(k_p = 0) = G_E(k_p = 0)$$

$$f_{L'}^{\bar{p}p}(k;E_k) = f_{L'}^{\bar{p}p;0}(k) + \sum_L \int_0^\infty \frac{dpp^2}{(2\pi)^3} f_L^{\bar{p}p;0}(p) \frac{1}{2E_k - 2E_p + i0^+} T_{LL'}^{\bar{p}p}(p,k;E_k)$$

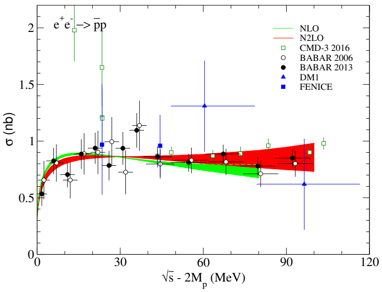
$f_{L'}^{\bar{p}p;0}$ ... bare vertex with bare form factors G_M^0 and G_E^0

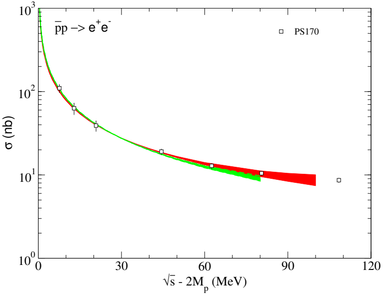
- assume $G_M^0 \equiv G_E^0 = \mathrm{const.}$ ... only single parameter (overall normalization)

Results for $e^+e^- \leftrightarrow \bar{p}p$

JH, X.-W. Kang, U.-G. Meißner, NPA 929 (2014) 102 (N^2LO)

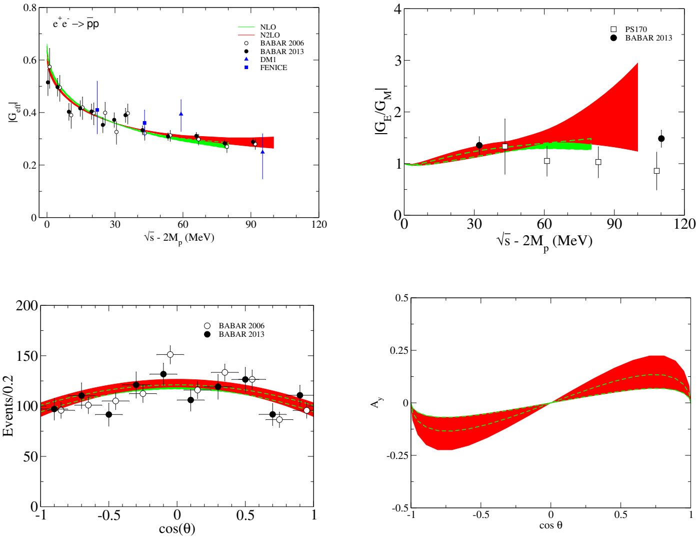
Note: here bands represent cutoff variations!





PS170: G. Bardin et al., NPB 411 (1994) 3

Results for $e^+e^- \to \bar{p}p$

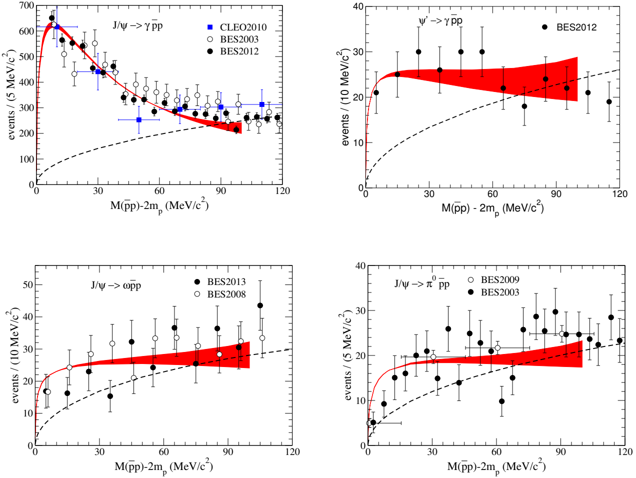


$\epsilon = \sqrt{s} - 2M_p = 36.5$ MeV

Other channels with $\bar{p}p$ in final state

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

bands represent cutoff variations!



Summary

- $\bar{N}N$ 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

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

- try an own PWA?
- new data $\bar{N}N$ data?