Antinucleon-Nucleon Interaction and Related Hadron Physics

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Outline

Introduction

- Potential models describe the low energy $\overline{N}N$ scattering successfully Nijmegen, Paris, Bonn/Jülich [Hippchen et al., PRC1989; 1991)].

  However, only little work of *$\overline{N}N$ interaction in chiral EFT* has been done.

- A renewed interest: experimental observations of the threshold enhancement in several decay channels, $J/\psi \to \gamma \bar{p}p$ etc., $e^+e^- \leftrightarrow \bar{p}p$ and $e^+e^- \to$ multipions.

- $\bar{p}p$ scattering experiments $\Rightarrow$ Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany

Contact terms (short-distance physics)

[Kang, Haidenbauer, Meißner, JHEP(2014)]

▷ pion-exchange contributions follows closely from NN case, except for the sign difference due to $G-$parity transformation.

▷ taking $^1S_0$ as an example, other partial waves can be done similarly.

(1) elastic part: *the same structure as the NN case*

$$V_{\rm ct}(^1S_0) = \tilde{C}_{^1S_0} + C_{^1S_0}(p^2 + p'^2)$$

(2) annihilation: *unitarity is built in!*

$$V_{\rm ann}(^1S_0) = -i\,(\tilde{C}^a_{^1S_0} + C^a_{^1S_0}p^2)(\tilde{C}^a_{^1S_0} + C^a_{^1S_0}p'^2)$$

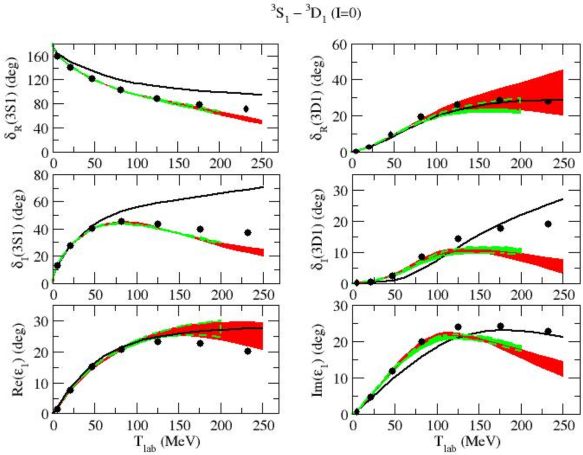
since

$$V_{\rm ann} = \sum_{X=2\pi,3\pi,\ldots} V_{\overline{N}N\to X}\, G_X(z)\, V_{X\to\overline{N}N}$$

$$G_X(z) \sim \frac{1}{z+i\epsilon} = \mathcal{P}\frac{1}{z} - i\pi\delta(z) \leftarrow \text{Cauchy theorem}$$

- unitarity leads to terms of formally higher orders!
- Contact terms are fixed by fitting to the partial wave amplitudes. [Zhou and Timmermans, PRC 86, 044003 (2012)]

Isospin-0 $^3S_1 - {}^3D_1$

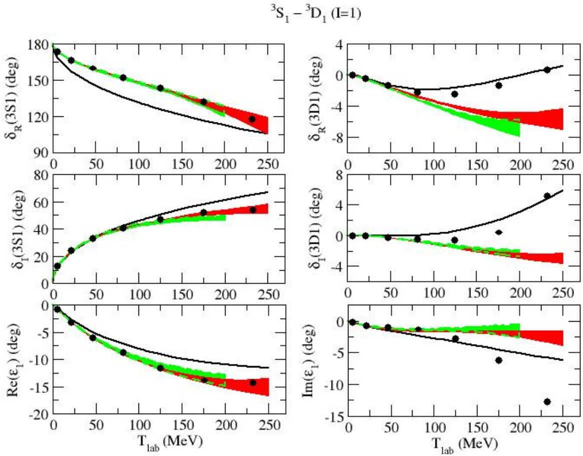


δ_R; $\quad \delta_I = -\log(\eta)/2$; $\qquad \epsilon_1$: mixing angle

black circle: PWA2012 $\qquad$ black line: Jülich A(OBE)

green band: NLO $\qquad$ red band: NNLO

Isospin-1 $^3S_1 - ^3D_1$



δ_R; $\delta_I = -\log(\eta)/2$; ϵ_1: mixing angle

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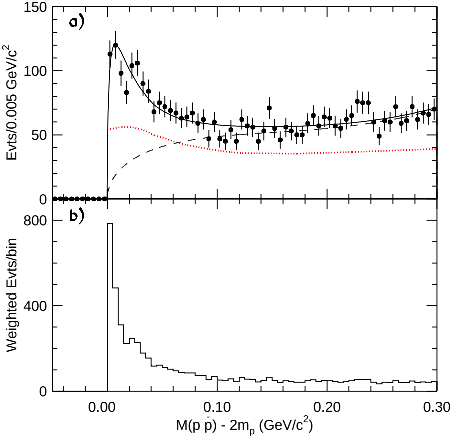
$p\bar{p}$ threshold enhancement

decay channel $J/\psi \to \gamma p\bar{p}$: Bai et al. [BES collaboration], PRL 91 (2003) 022001.

events $\times\ q_0/q$

$q_0 \hat{=} M_{p\bar{p}} = 2$ GeV/c^2



▷ glueball: Chua et al (2002); J. L. Rosner (2003)

▷ bound states [final state interactions]

$\bar{p}p$ final state interaction: formalism

[Kang, Haidenbauer, Meißner, PRD(2015)]

$$A = A^0 + A^0 G_0 T_{\overline{N}N},$$

A^0 : production amplitude, *constant at near-threshold region*

G_0 : free $\overline{N}N$ Green's function

T : $p\bar{p}$ scattering T-matrix elements, cf. last part

▷only an overall normalization constant!

channels	lowest partial waves	isospin
$J/\psi \to \gamma p\bar{p}$	${}^1S_0$	0, 1
⋮		

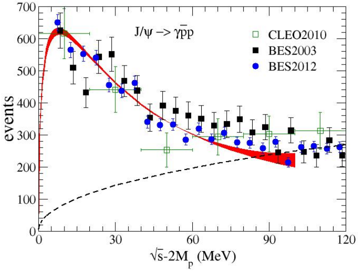
Radiative decay

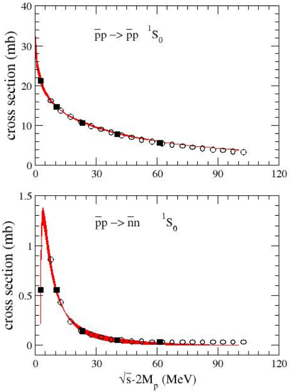
black dashed: phase space behavior

red band: NNLO

solid square: PWA2012

open circle: Kang et al.(2014)





▷ total cross section calculated, in a good agreement with data

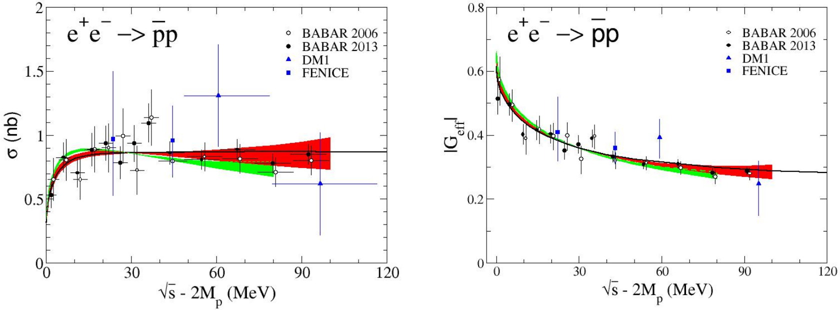
▷ the data for protonium level shifts and widths are reproduced

▷ $\bar{p}p$ bound state is found in isospin-1 $^1S_0$.

[Haidenbauer, Kang, Meißner, NPA(2014)]

black line: Jülich A(OBE)

green band: NLO red band: NNLO



▷ calculated (predicted) differential cross sections agree with data very well

▷ EM form factors (ratio and relative phase) are also calculated.

dips in $e^+e^- \to$ multipions: formalism

[Haidenbauer, Hanhart, Kang, Meißner, arXiv2015]

$$
\begin{aligned}
T_{e^+e^-\to n\pi} &= V_{e^+e^-\to n\pi} + T_{e^+e^-\to \bar{N}N} G_0 V_{\bar{N}N\to n\pi} \\
T_{\bar{N}N\to n\pi} &= V_{\bar{N}N\to n\pi} + T_{\bar{N}N\to \bar{N}N} G_0 V_{\bar{N}N\to n\pi} \\
T_{\bar{N}N\to \bar{N}N} &= V_{\bar{N}N\to \bar{N}N} + V_{\bar{N}N\to \bar{N}N} G_0 T_{\bar{N}N\to \bar{N}N} \\
\sigma(s) &= \frac{3s\beta}{2^{10}\pi^3}|T|^2, \beta = p_f/p_i \text{ : phase space factor}
\end{aligned}
$$

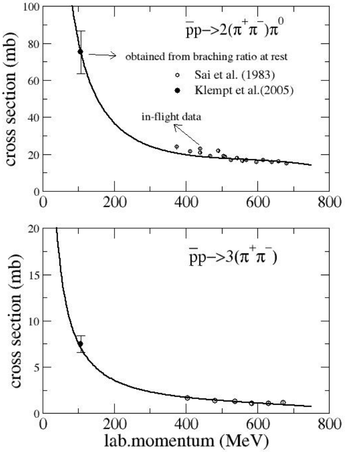
keypoints:

- $T_{\bar{N}N\to\bar{N}N}$ has been studied before
- $T_{e^+e^-\to\bar{p}p}$ has been studied before
- fix $V_{\bar{N}N\to n\pi}$ to the corresponding cross section (data available); in $\bar{N}N \to n\pi$, assume a specific partial wave ($^3S_1$) dominates,

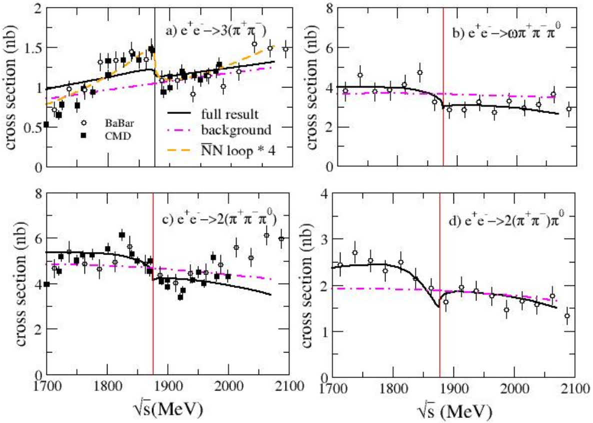
▷ thus loop contribution is calculated reliably — every term is fixed by the external experimental source.

approximation: effective two-body phase

$\bar{p}p \to$ multipions: fitting



$$V_{\bar{p}p\to 3(\pi^+\pi^-)} = c_0,$$
$$V_{\bar{p}p\to 2(\pi^+\pi^-)\pi^0} = \tilde{c}_0 + \tilde{c}_2 q^2$$


a) e+e-->3(π+π-)
b) e+e-->ωπ+π-π0
c) e+e-->2(π+π-π0)
d) e+e-->2(π+π-)π0
BaBar
CMD
full result
background
N̄N loop * 4
cross section (nb)
√s(MeV)
√s (MeV)

Summary

- Chiral effective field theory works well for $\overline{N}N$ scattering
  - Phase shifts for PWA are nicely reproduced up to $T_{\rm lab} = 200$ MeV
  - The predicted scattering lengths agrees well with "experimental" value
- $\bar{p}p$ threshold effects
  - strongly enhanced near-threshold $\bar{p}p$ mass spectra observed in $J/\psi \to \gamma p\bar{p}$ is well described by our treatment of FSI
  - low-energy $\sigma(e^+e^- \to \bar{p}p)$ is reproduced by inclusion of $\bar{p}p$ FSI. Proton form factor in the time-like region is calculated at low energies
  - dip structure around $\bar{p}p$ threshold observed in $e^+e^- \to$ multipions is due to an opening of $\overline{N}N$ channel

Weinberg power counting

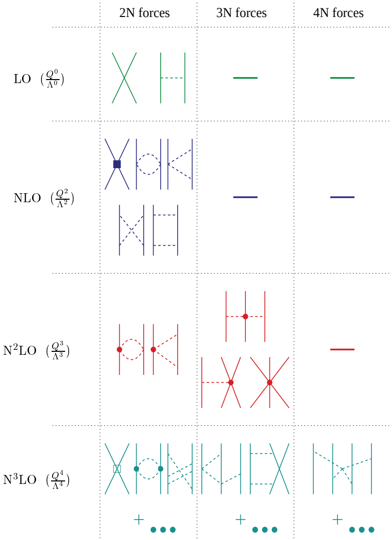
- in the low momentum expansion, potential V receives contributions $V \sim (Q/\Lambda)^\nu$;

  Q: soft scale (external momentum or pion mass),
  Λ: hard scale (chiral symmetry breaking scale $\sim$ 1 GeV).

- two-body problem NN or $\overline{N}N$ (elastic part): $\nu = 2L + \sum_i \Delta_i$
  - L = number of loops,
  - $\Delta_i = d_i + \frac{n_i}{2} - 2$

    d_i =number of derivatives and/or insertions of M_π,
    n_i = number of nucleon field operators.

Hierarchy of nuclear forces

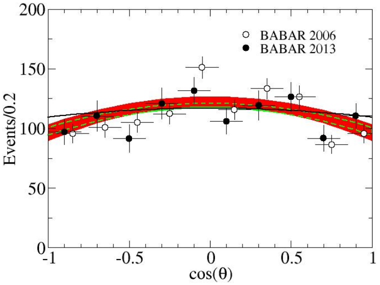


Meißner, NPA 751, 149 (2005)

$e^+e^- \leftrightarrow \bar{p}p$: differential cross sections

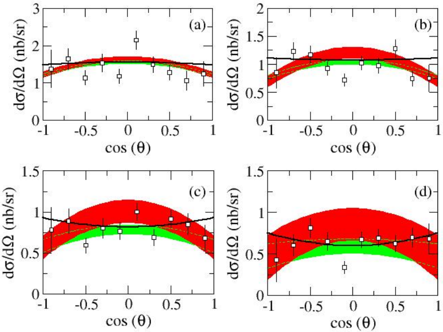
black line: Jülich A(OBE)

green band: NLO   red band: NNLO



$e^+e^- \rightarrow \bar{p}p$ (BABAR)

$T_{\text{lab}} = 36.5$ MeV

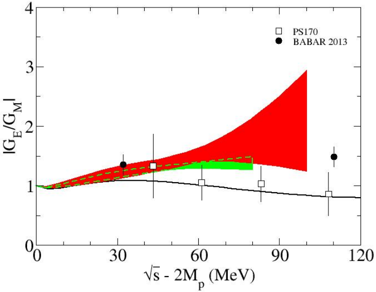


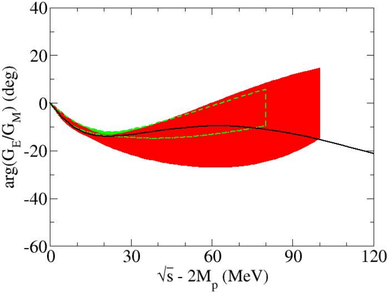
$\bar{p}p \rightarrow e^+e^-$ (PS170)

(a) 43.5 MeV (b) 62.6 MeV
(c) 80.9 MeV (d) 107.5 MeV

black line: Jülich A(OBE)

green band: NLO red band: NNLO





- phase difference between G_E and G_M is shown as prediction.
- experimental status will be improved by VEPP-2000 collider in Novosibirsk, Russia and FAIR in Darmstadt, Germany.
- VEPP: currently about 6 pb^{-1} $\bar{p}p$ from threshold to 2 GeV, with planned data of 1 fb^{-1}.