低エネルギー反中性子散乱実験による
反中性子-陽子（原子核）間相互作用の研究

藤岡　宏之（東京科学大学）

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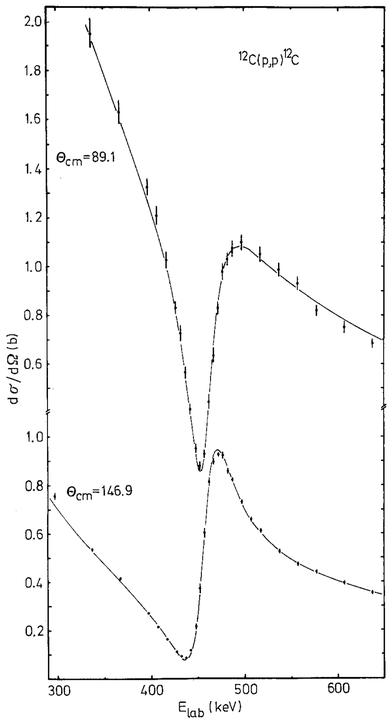
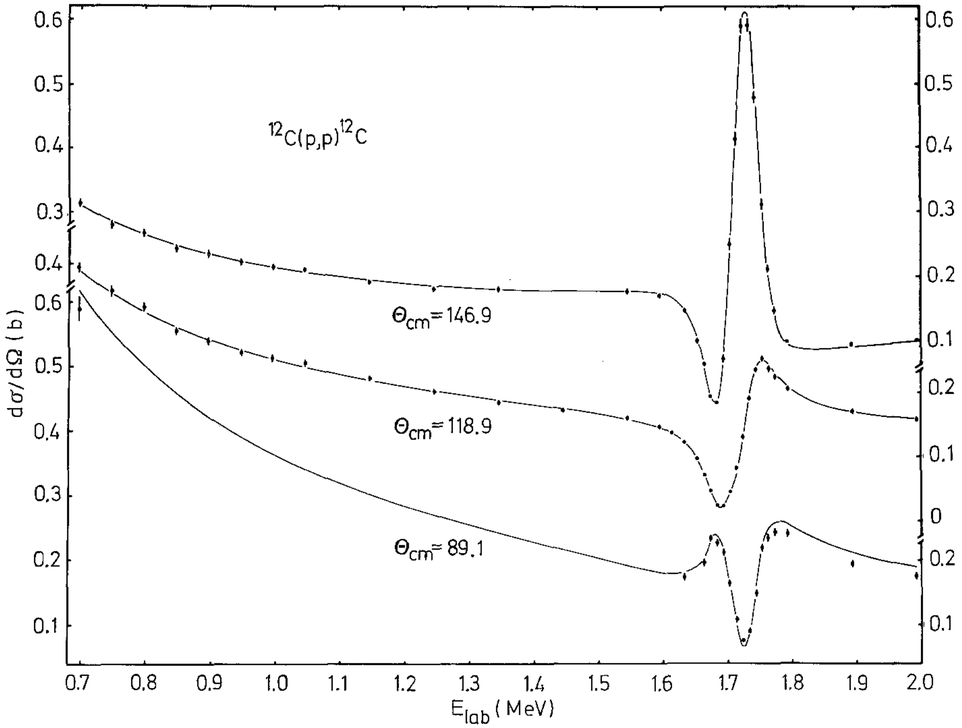
低エネルギー核子原子核散乱

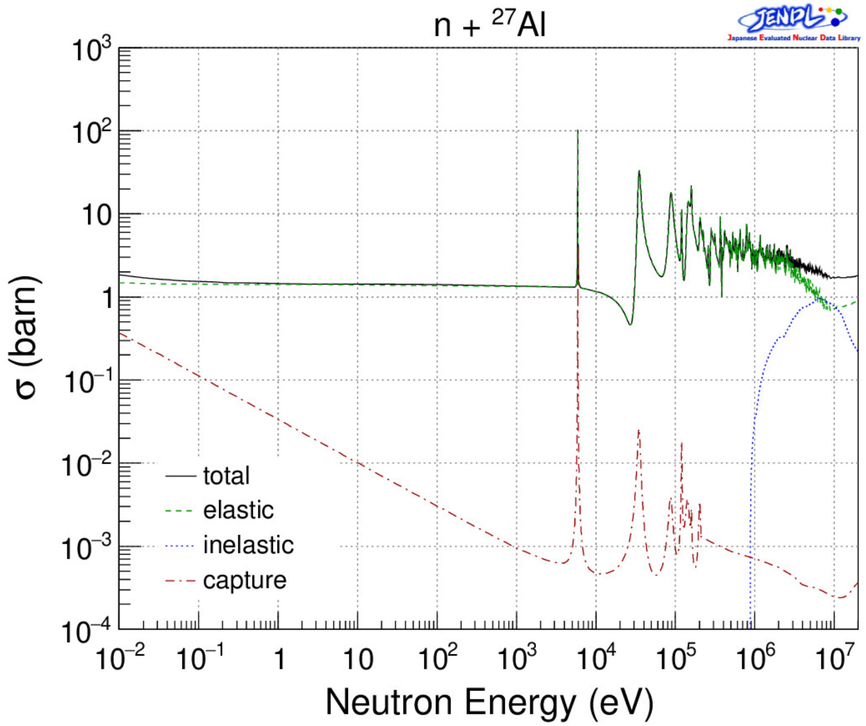
p+^{12}C





H. Meyer, G. Plattner, and I. Sick, Z. Phys. A279, 41 (1976)

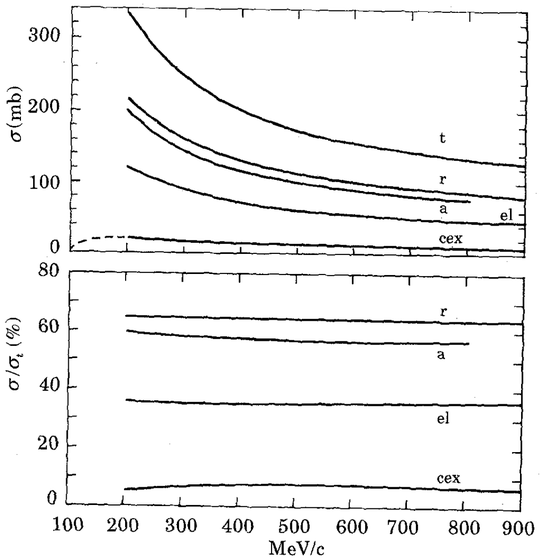
n+^{27}Al

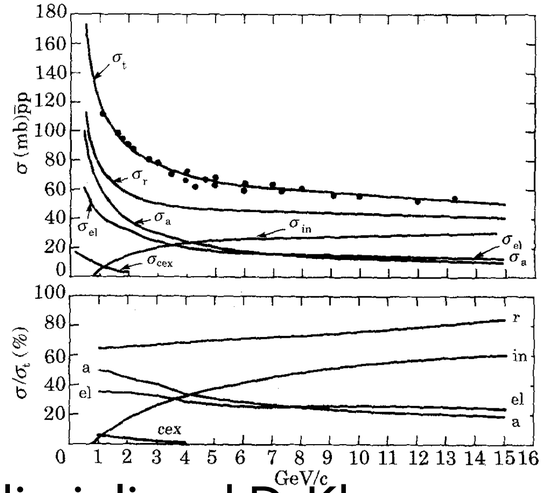


JENDL-5

低エネルギー核子散乱と反核子散乱の違い

- 弾性散乱以外の反応：対消滅 ($\bar{N}N \to$ multiple π's etc.) が支配的
  - cf. 荷電交換反応 $\bar{p}p \to \bar{n}n$ の反応閾値は 98 MeV/c (5.1 MeV)
- 強い吸収：$|V_0| \lesssim |W_0| \sim \mathcal{O}(10^2)\,\mathrm{MeV}$
- 断面積のエネルギー依存性は単調：狭い共鳴は存在しない





G. Bendiscioli and D. Kharzeev,
Riv. Nuovo Cimento 17, 1 (1994)

Executive Summary (1)

- **We propose to construct a new beamline at CERN-AD for antineutrons with unprecedented low energies (p=9MeV/c, E=40keV)**
- **Physics cases:**
  - antineutron–proton ($\bar{n}p$) scattering ⇒ isospin-1 $N\bar{N}$ interaction
  - antineutron–nucleus ($\bar{n}A$) scattering ⇒ antineutron–nucleus interaction
- References:
  - A. Filippi, HF, T. Higuchi, L. Venturelli, arXiv:2503.06972 [nucl-ex]
  - C. Amsler *et al.*, Letter of Intent, CERN-SPSC-2025-010, SPSC-I-261 (May 2025)
  - HF and T. Higuchi, Prog. Theor. Exp. Phys. 2026, 023C01 (2026)

Overview

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antineutron–proton system **antineutron–nucleus system**

cross-section measurements: $\sigma_{\mathrm{el}}, \sigma_{\mathrm{ann}}, \sigma_{\mathrm{tot}}$

scattering theory (s-wave)

$\ell = R \cdot p < \hbar/2$

R~(nuclear size)<10 fm

p~9 MeV/c

$\sigma_{\mathrm{el}} \approx 4\pi |a|^2 (1 - 2a_{\mathrm{I}}k)$

$\sigma_{\mathrm{ann}} \approx \frac{4\pi}{k} a_{\mathrm{I}} - 8\pi a_{\mathrm{I}}^2$

low-energy is the key for the evaluation of scattering lengths!

hadron physics

BSM physics

scattering length: $a_{\bar{n}p}$

cf. antiproton-proton scattering,
protonium (antiproton-proton bound system)

comparison

NN̄ interaction models

antineutron-nucleus optical potential

$U(r) = V(r) - iW(r)$

cf. antiproton-nucleus scattering,
antiprotonic atom spectroscopy

scattering length: $a_{\bar{n}A}$

Fermi pseudopotential for ultracold antineutrons

$U_{\bar{n}} = \frac{2\pi\hbar^2}{m} N \frac{A+1}{A} a_{\bar{n}A}$

input

"ultracold" < 200 neV

n-n̄ oscillation search

Executive Summary (2)

- **The ASACUSA experiment at CERN-AD plans to measure antiproton-nucleus cross sections at 100 keV (~14 MeV/c) in near future.**
- **Physics cases:**
  - antiproton–nucleus ($\bar{p}A$) scattering ⇒ antiproton–nucleus interaction
  - prospect: antiproton–proton ($\bar{p}p$) scattering using carbon and CH_2 targets
- References:
  - H. Aghai-Khozani et al., Nucl. Phys. A 970, 366 (2018) @ 5.3 MeV
  - H. Aghai-Khozani et al., Nucl. Phys. A 1009, 122170 (2021) @ 125 keV

NN interaction and N$\bar{N}$ interaction

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- One-boson-exchange models
  - $V_{NN} = V_\pi + V_{2\pi} + V_\eta + V_\rho + V_\omega + \cdots$

    ↓ G-parity transformation

    $V_{N\bar{N}} = -V_\pi + V_{2\pi} + V_\eta + V_\rho - V_\omega + \cdots$
  - The short-range part is replaced by an annihilation potential $V_0 + iW_0$
    - NN Paris potential → N$\bar{N}$ Paris potential
    - Dover-Richard, Kohno-Weise, … :Woods–Saxon-type annihilation potential
- Partial Wave Analysis [PRC 86 (2012) 044003]
- Chiral EFT [up to N^{3}LO, JHEP 07(2017) 078]
- no Lattice QCD calculation
- All these approaches rely on experimental data, that are more than three decades old.

NN̄ optical potential and phase shift

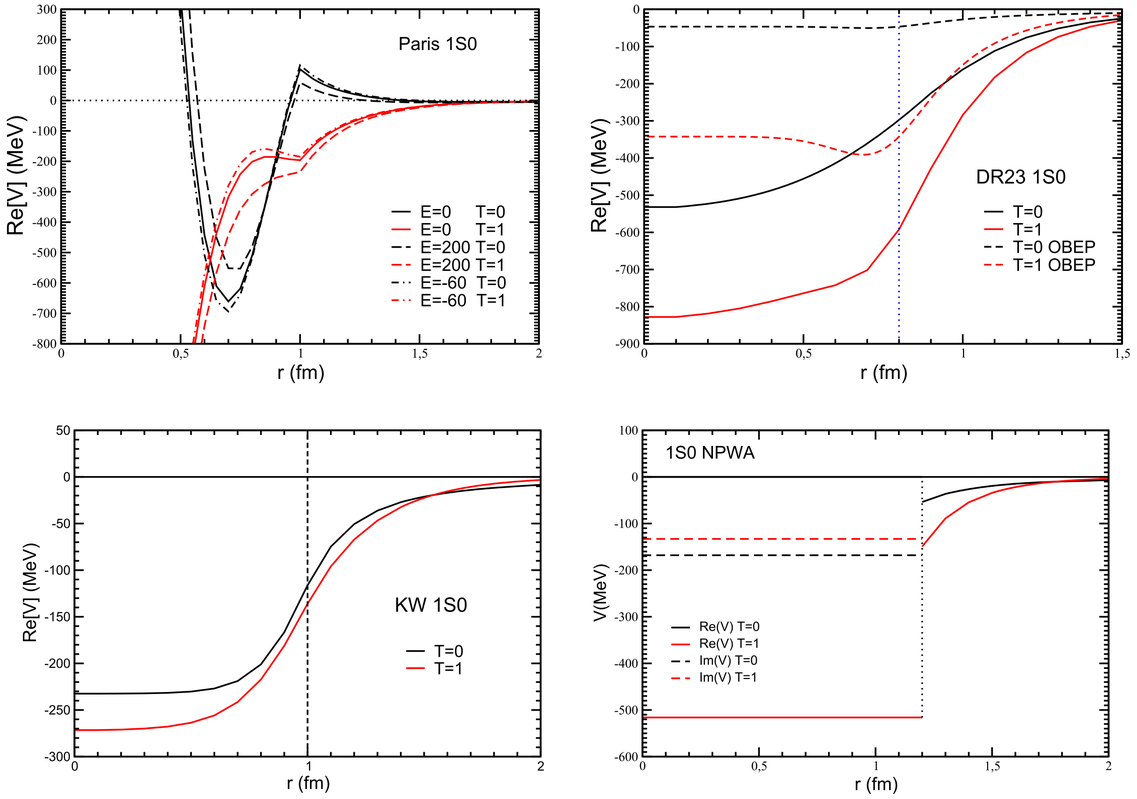


Fig. 15 Real parts of $^{1}S_{0}$ potentials for both isospins (T)

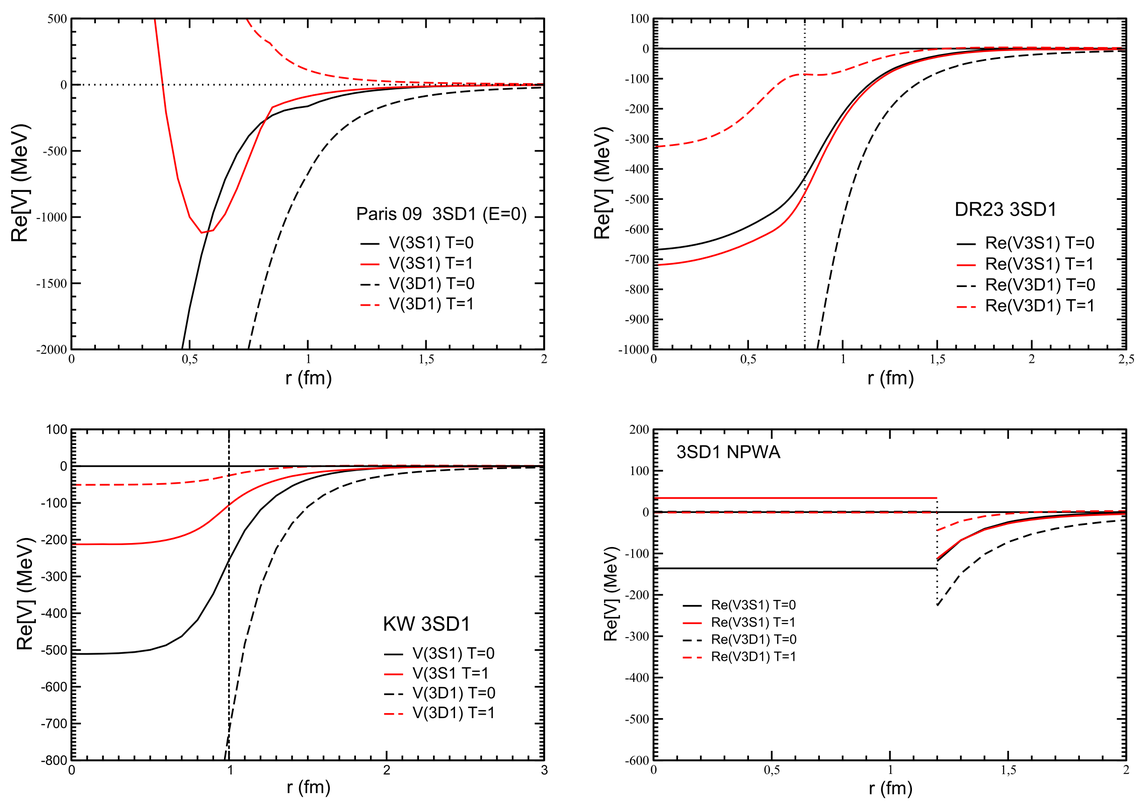
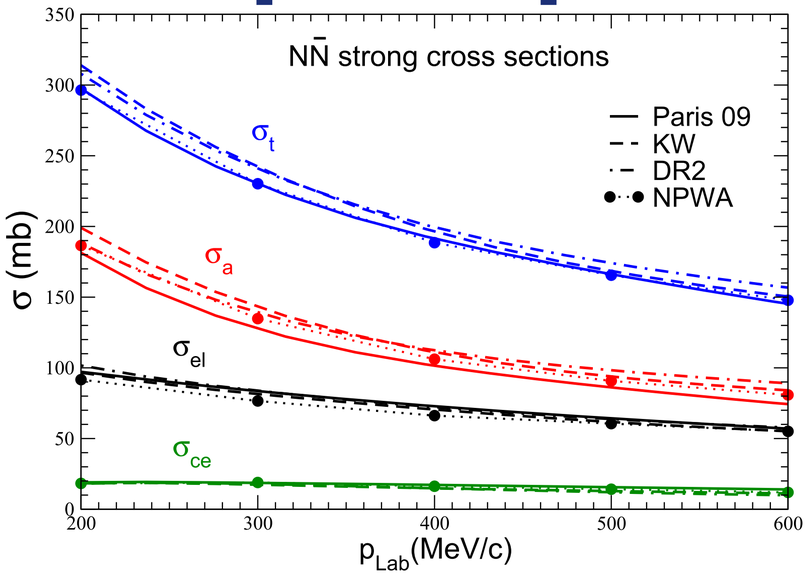
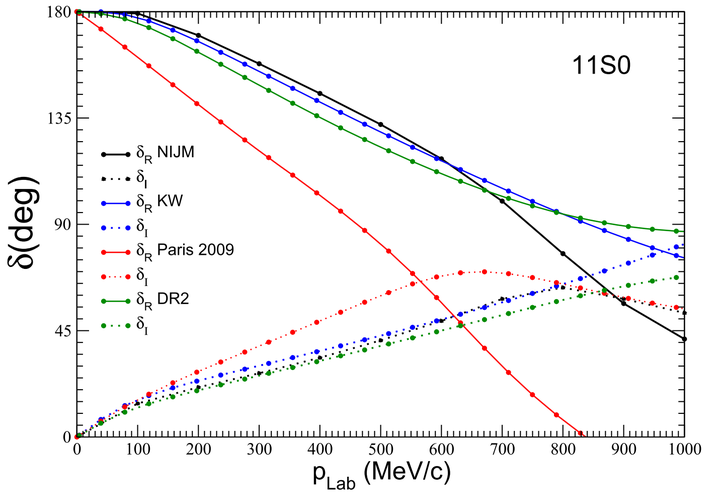


Fig. 16 Real parts of $^{3}S_{1}$ and $^{3}D_{1}$ potentials for both isospins (T)

J. Carbonell et al., EPJ A 59 (2023) 259

NN̄ optical potential and phase shift





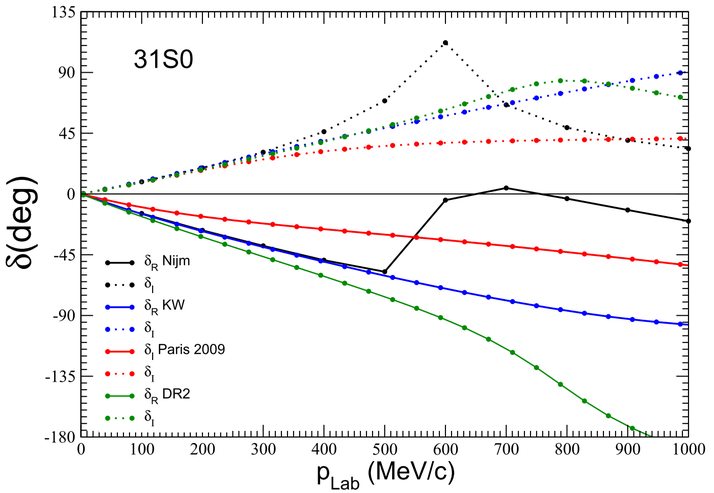
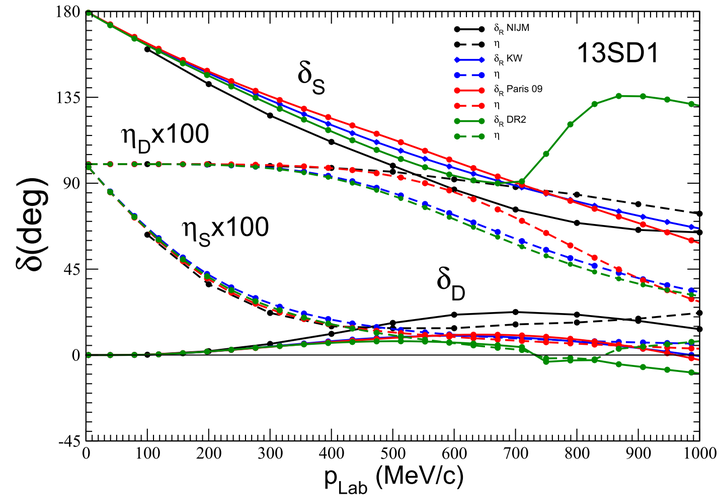
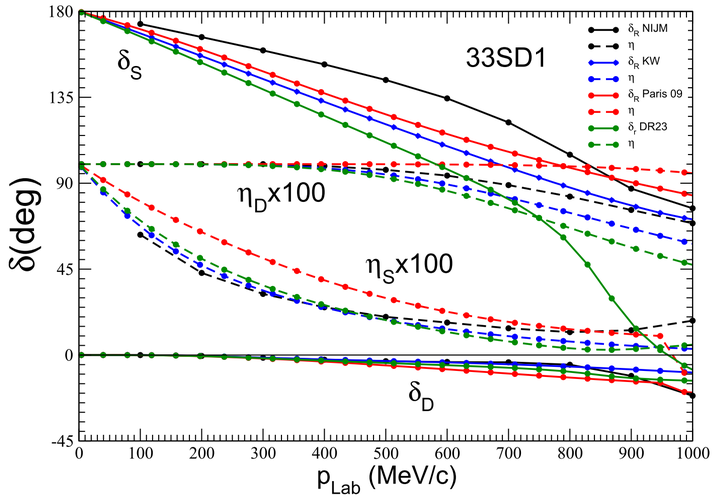


Table 2 S-wave N̄N low energy parameters (in fm) for the considered optical models: Jülich results are taken from Table 3 of Ref. [12], KW and DR2 from [20], Paris 2009 have been recomputed and are in agreement with [46]. The values of Nijmegen are obtained by extrapolating the phase shifts from Figs. 2 and3

T = 0	a_0 $^{11}S_0$	r_0	a_0 $^{13}SD_1$	r_0
Nijm*	–0.17 -1.01i	–6.9-2.9 i	–	–
Jülich	–0.21 –1.23i	–	1.42-0.88i	–
Paris 09	1.27 –1.18i	–0.53+0.14i	1.20–0.80i	–
KW	–0.03–1.35i	–4.7–7.9i	1.23–0.77i	–
DR2	0.10 –1.07i	–11–6.2i	1.28–0.78i	–
T = 1	$^{31}S_0$		$^{33}SD_1$	
Nijm*	1.02 –0.60i	0.7–1.2i	–	–
Jülich	1.05 –0.58i	–	0.44–0.96i	–
Paris 09	0.76 –0.56i	0.9–3.9i	0.61–0.44i	–
KW	1.07 –0.62i	0.7–1.9i	0.78–0.80i	–
DR2	1.20 –0.57i	0.6–1.6i	0.89–0.71i	–





J. Carbonell et al., EPJ A 59 (2023) 259

Partial Wave Analysis

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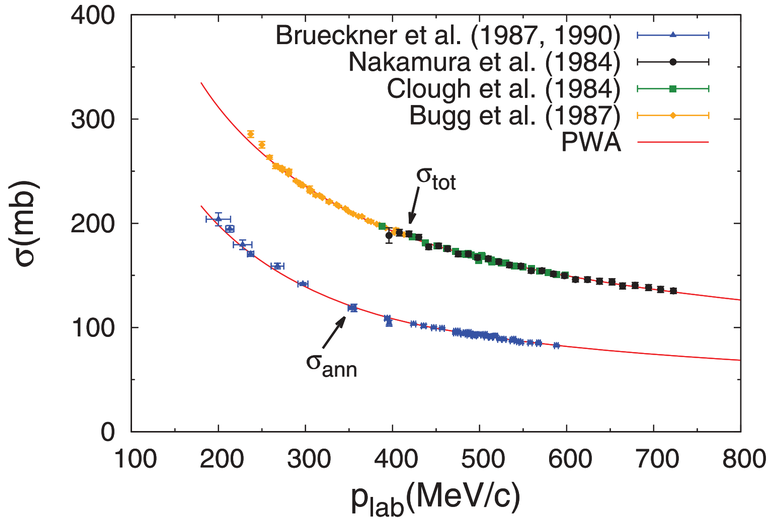
- for elastic ($p\bar{p} \to p\bar{p}$) and charge-exchange ($p\bar{p} \to n\bar{n}$) scattering data

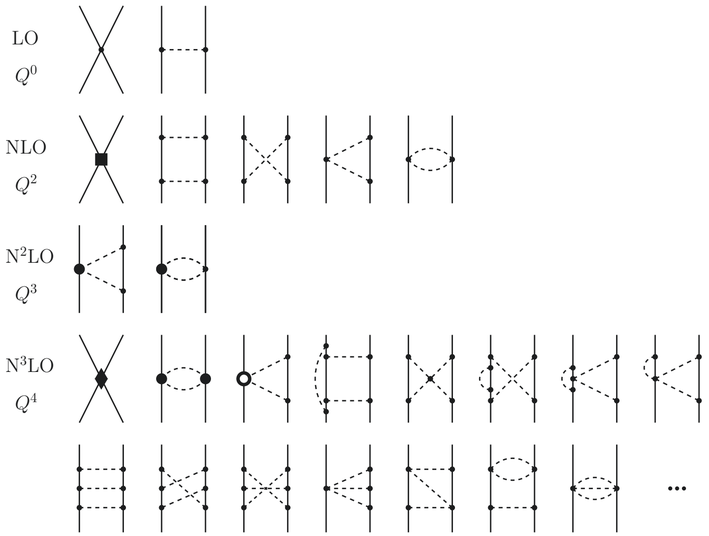
TABLE III. Reference table of antiproton-proton scattering data with $p_{\rm lab} \leqslant 923$ MeV/c. The asterisks in the leftmost column indicate the data sets that were not included in Ref. [23], because the data are more recent or because the values of the data points were not available. The meanings of the superscripts in the heading and the comments in the rightmost column are given at the end of the table.

$p_{\rm lab}$ (MeV/c)	No.,[a] type[b]	$\chi^2_{\rm min}$	Norm error (%)[v]	Predicted norm[c]	Rejected[d]	Ref.	Comment
119.0–923.0	50 $\sigma_{\rm ce}$	46.5	4	1.058	$\leqslant$385.0, #=8; 468.0	[45]	k,m
176.8–396.1	5 $\sigma_{\rm ann}$	9.4	4.4	0.949	176.8	[46]	
181.0	46 d$\sigma_{\rm el}$	–	5	–	All	[47,48]	j,l,o
183.0	13 d$\sigma_{\rm ce}$	13.3	5	1.002	0.940,−0.170,−0.574	[49]	
194.8	19 d$\sigma_{\rm el}$	–	4	–	All	[50]	f,i,o
200.0–588.2	48 $\sigma_{\rm ann}$	52.5	2.2	0.989		[46,51]	
221.9–413.2	45 $\sigma_{\rm tot}$	55.3	∞	0.961	221.9, 229.6, 254.9, 260.8, 280.3, 289.1, 394.2, Norm	[52]	
				•			
				•			
				•			
875.0*	9 $D_{yy,{\rm ce}}$	5.1	–	–		[74,88]	q
875.0*	5 $K_{yy,{\rm ce}}$	5.9	–	–		[89]	q
886.0	34 d$\sigma_{\rm el}$	–	∞	–	All	[71]	h,l
886.0	34 $A_{y,{\rm el}}$	34.1	4.5	1.023		[70,71]	
886.0	1 $D_{yy,{\rm el}}$	1.5	–	–		[79]	q
910.0	19 d$\sigma_{\rm el}$	–	∞	–	All	[90]	f,g
910.0	21 $A_{y,{\rm el}}$	12.9	5	0.990		[90]	



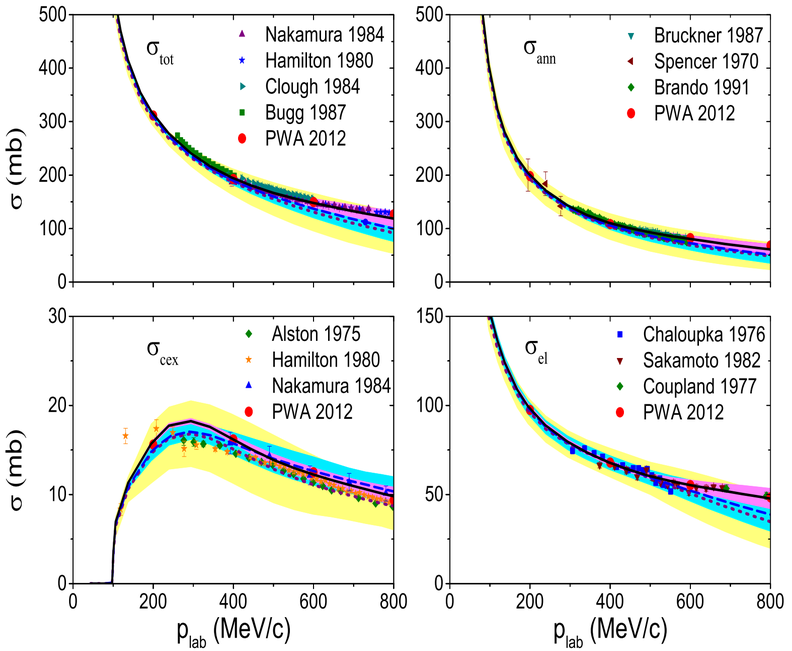
D. Zhou and R. G. E. Timmermans, Phys. Rev. C 86, 044003 (2012)

Chiral Effective Field Theory



N^{2}LO: X.-W. Kang, J. Haidenbauer, U.-G. Meißner, JHEP 02, 113 (2014)

N^{3}LO: L.-Y. Dai, J. Haidenbauer, U.-G. Meißner JHEP 07, 078 (2017)



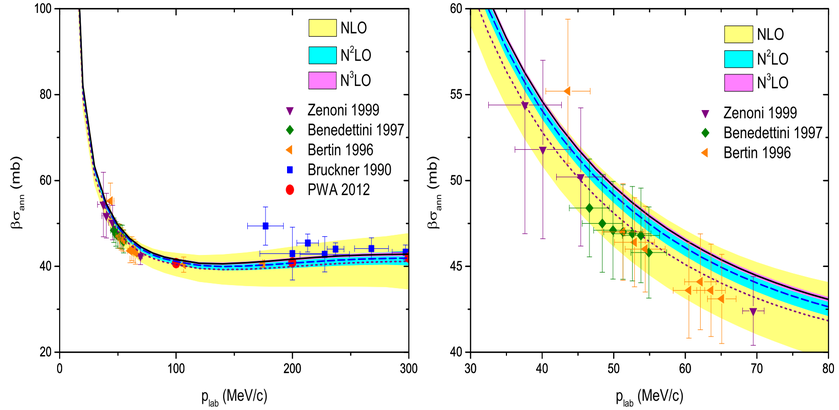


Figure 14. $\bar{p}p$ annihilation cross section multiplied by the velocity β of the incoming $\bar{p}$. Notations are described in the text. The results of the PWA [32] are indicated by circles. Data are taken from [104–107].

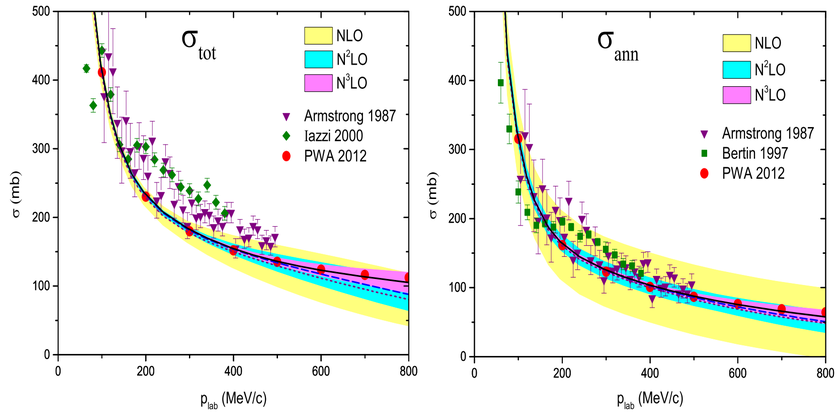
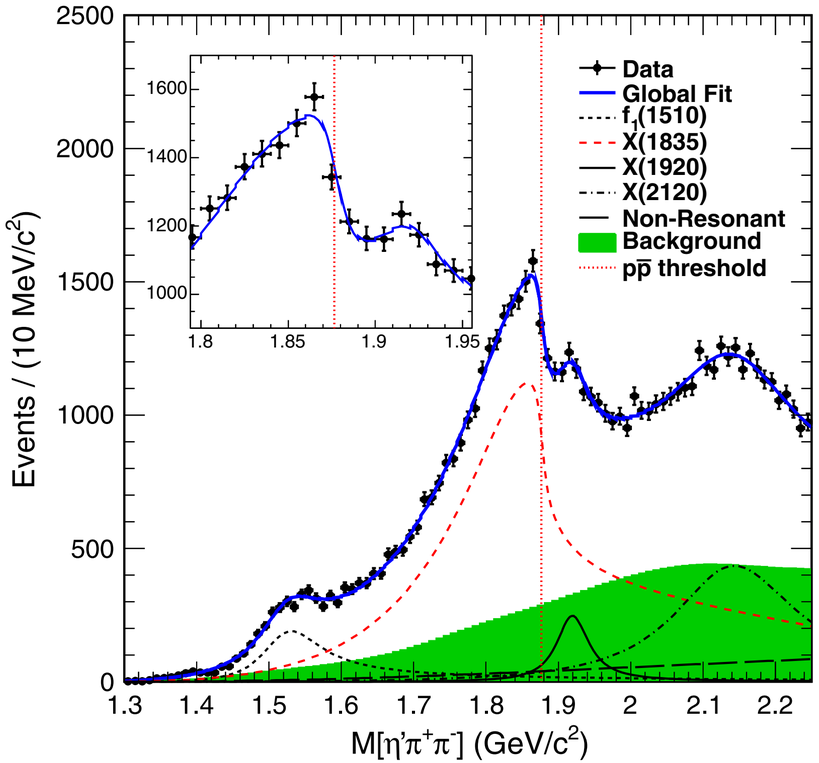


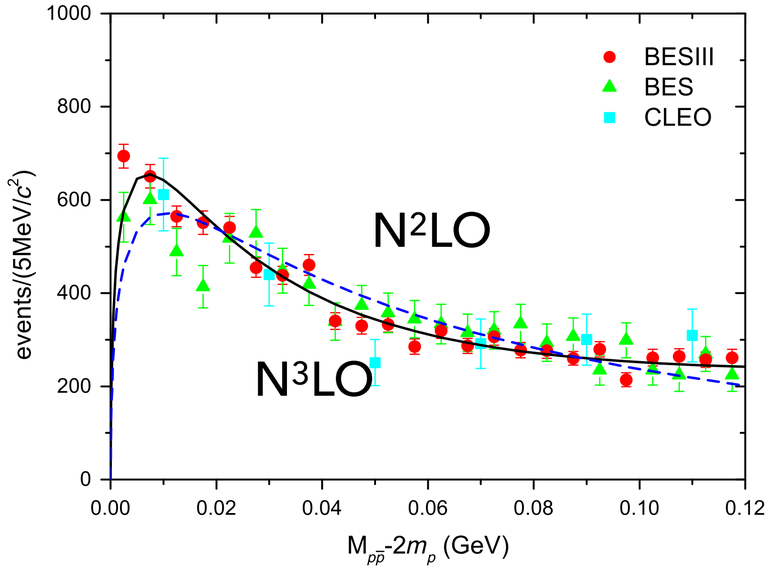
Figure 15. Total ($\sigma_{\rm tot}$) and integrated annihilation ($\sigma_{\rm ann}$) cross sections for $\bar{n}p$ scattering. Notations are described in the text. Data are taken from refs. [109–111].

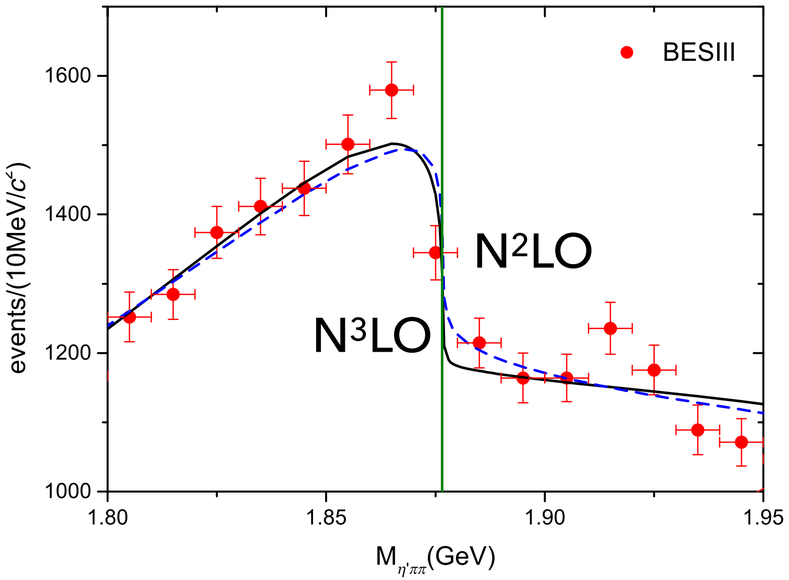
X(1835) or pp̄ FSI in J/ψ decay?

$$J/\psi \to \gamma p\bar{p} \to \gamma \eta' \pi^+ \pi^-$$



BESIII Collaboration, Phys. Rev. Lett. 117, 042002 (2016)



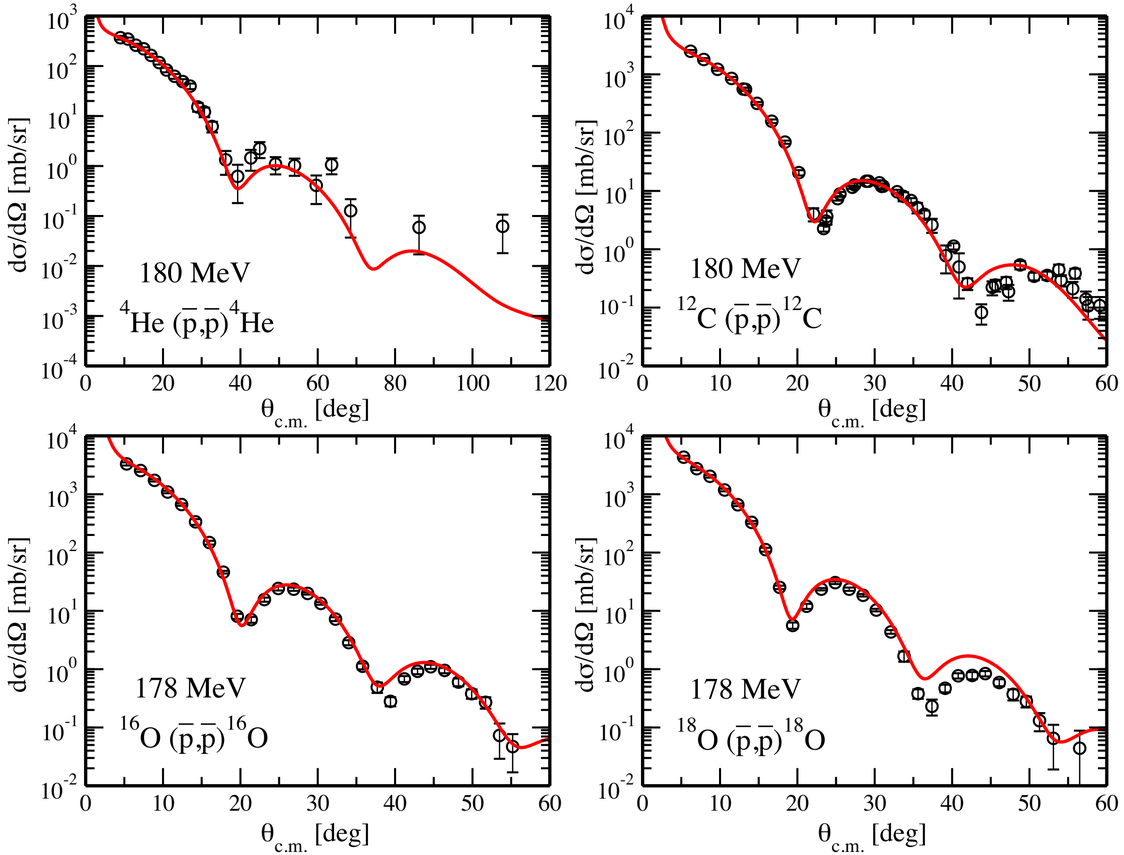


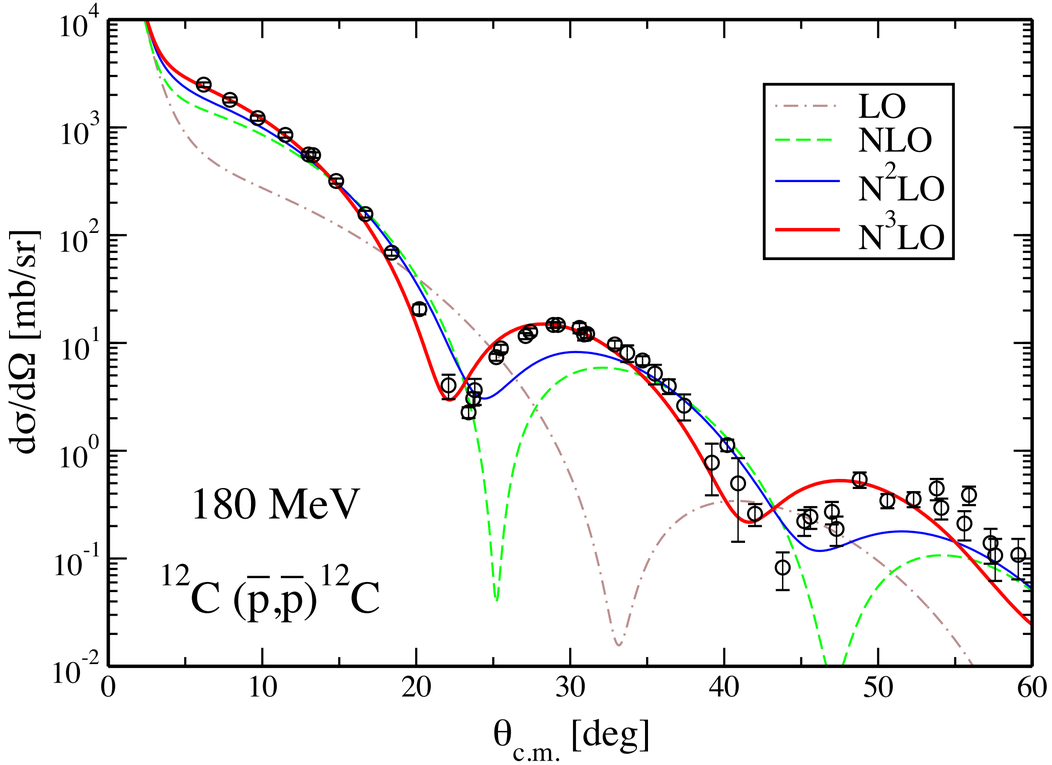
L.-Y. Dai, J. Haidenbauer, U.-G. Meißner, Phys. Rev. D 98, 014005 (2018)

Elastic scattering from Chiral Forces

- microscopic optical potential, constructed with chiral p̄N forces

  + nuclear densities obtained from *ab initio* calculations (NN and 3N interactions)

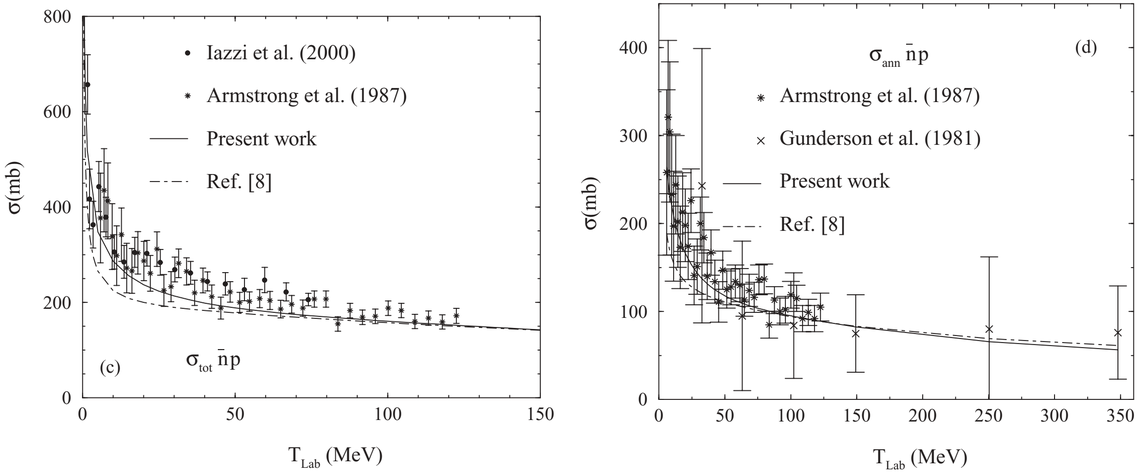




M. Vorabbi, M. Gennari, P. Finelli, C. Giusti, P. Navrátil, Phys. Rev. Lett. 124, 12501 (2020)

Low-energy $\bar{n}p$ scattering

- purely in the isospin=1 channel
- only adopted in a recent work on the Paris potential updated in 2009.



- Many parameters (spin, isospin, partial wave) have to be fixed in each model.

Paris '09: B. El-Bennich,[1,2] M. Lacombe,[1] B. Loiseau, and S. Wycech, Phys. Rev. C 79, 054001 (2009)

- We propose a model-independent approach to determine scattering lengths by low-energy scattering measurements.

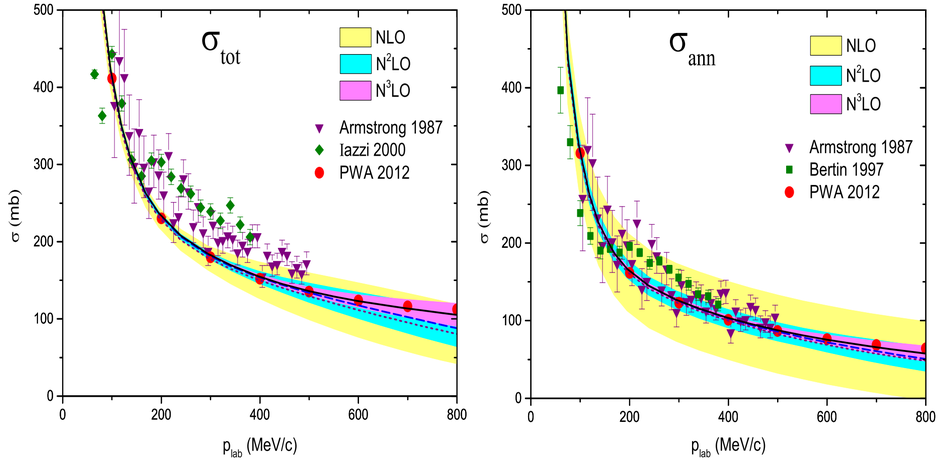


Figure 15. Total ($\sigma_{\rm tot}$) and integrated annihilation ($\sigma_{\rm ann}$) cross sections for $\bar{n}p$ scattering. Notations are described in the text. Data are taken from refs. [109–111].

Chiral EFT: L.-Y. Dai, J. Haidenbauer, U.-G. Meißner JHEP 07, 078 (2017)

Low-energy $\bar{n}p$ scattering

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- Only S-wave scattering is important in case of $\hbar k = p_{\mathrm{Lab}}/2 \lesssim 25\,\mathrm{MeV}/c$
- scattering amplitude: $f_{\ell=0} = 1/(k\cot\delta - ik)$
  - $k\cot\delta \approx -1/a \equiv \alpha = \alpha_{\mathrm{R}} - i\alpha_{\mathrm{I}}\ (\alpha_{\mathrm{I}} > 0)$ in the low-energy limit
  - scattering length: $a = a_{\mathrm{R}} - ia_{\mathrm{I}}\ (a_{\mathrm{I}} > 0)$

- elastic scattering cross section: $\sigma_{\mathrm{el}} = \dfrac{4\pi}{\alpha_R^2 + (\alpha_I + k)^2} \approx 4\pi|a|^2(1 - 2a_{\mathrm{I}}k)$
- annihilation cross section: $\sigma_{\mathrm{ann}} = \dfrac{4\pi}{k}\dfrac{\alpha_{\mathrm{I}}}{\alpha_R^2 + (\alpha_I + k)^2} \approx \underline{\dfrac{4\pi}{k}a_{\mathrm{I}}} - 8\pi a_{\mathrm{I}}^2$

proportional to $1/v$

$\bar{n}p$ annihilation at OBELIX

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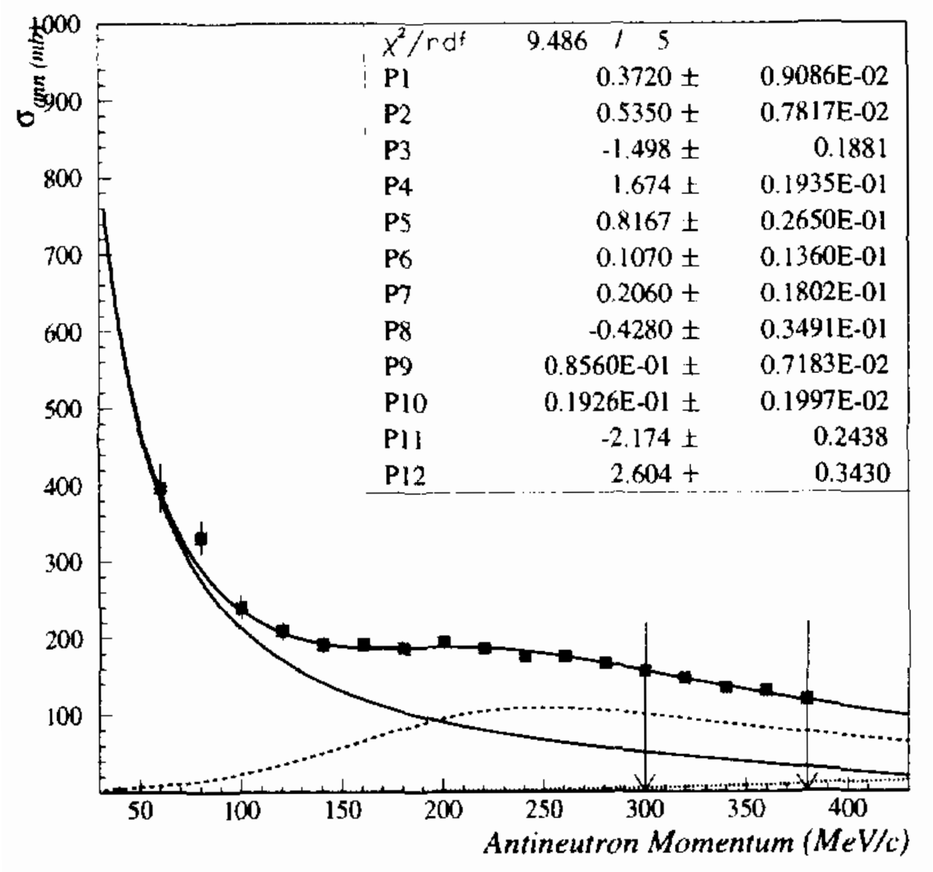
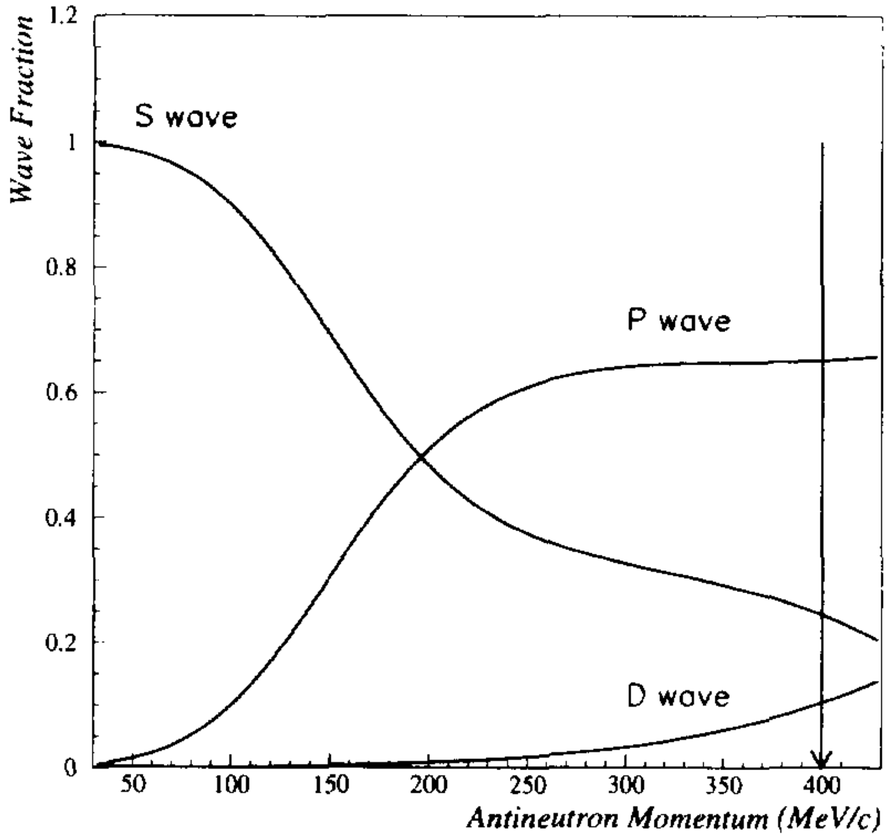
S, P and D-wave parameters from the fit of $\sigma_{ann}^{\bar{n}p}$ up to 400 MeV/c.

$a_1(fm)$	$r_1(fm)$	$b_1(fm^3)$	$R_1(fm)$	$c_1(fm^5)$	$\rho_1(fm)$	χ^2/n
$0.37 + i0.53$	$-1.5 + i1.67$	$0.82 + i0.11$	$0.21 - i0.43$	$0.086 + i0.019$	$-2.17 + i2.6$	$9.5/5$





A. Bertin et al., Nucl. Phys. B 56A (1997) 227c

Low-energy $\bar{p}p$ scattering (annihilation)

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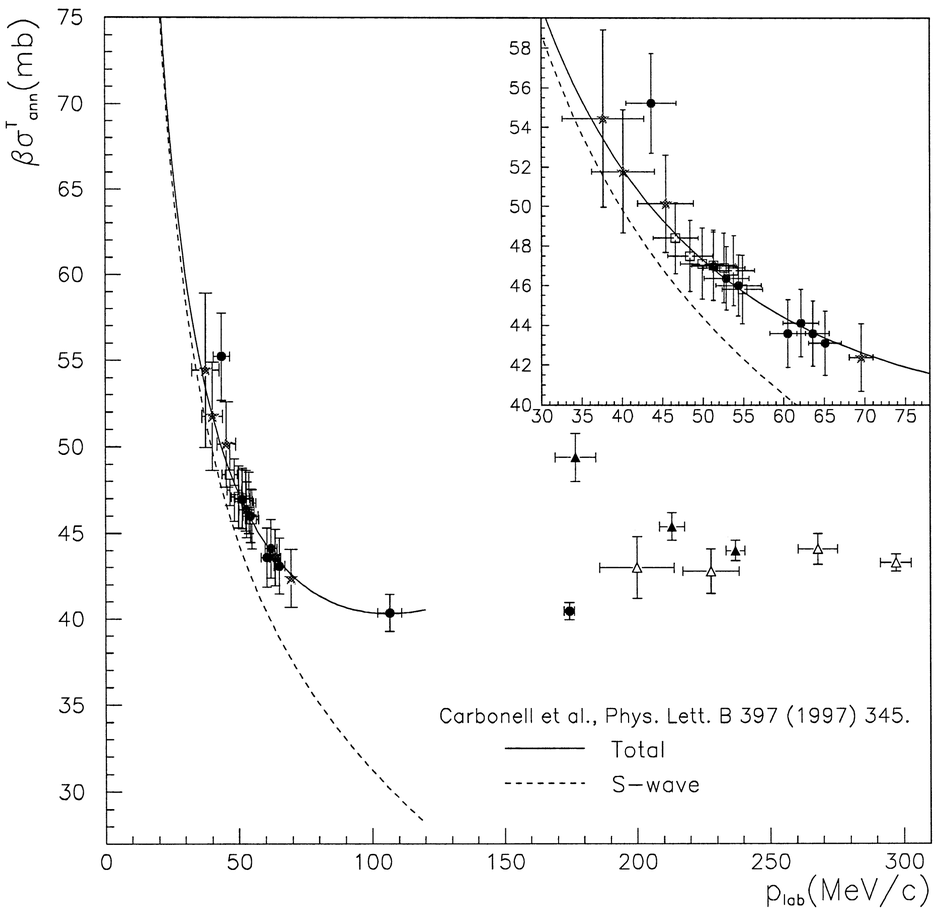
- Due to attractive Coulomb interaction
  - $\sigma \propto v^{-2}$ instead of $\sigma \propto v^{-1}$
  - p-wave doesn't vanish even when E→0
  - Coulomb-corrected scattering length a_{sc} can be deduced as follows:

$$q^2\sigma_{\text{ann}}^{sc}(\text{S-wave}) = \frac{8\pi^2}{1-e^{2\pi\eta}} \frac{\text{Im}\,(-a_{sc}/B)}{|1+iqw(\eta)a_{sc}|^2}, \quad (1)$$

where:
- $\eta = -1/qB$ is the dimensionless Coulomb parameter with B the $\bar{p}p$ Bohr radius;
- $w(x) = c_0^2(x) - 2ixh(x)$ is an auxiliary function with $qBw(\eta) \to 2\pi$ when $q \to 0$;
- c_0^2 and h are the usual functions in the Coulomb scattering theory

$$c_0^2(x) = \frac{2\pi x}{\exp(2\pi x)-1};$$

$$h(x) = \tfrac{1}{2}\left[\Psi(-ix)+\Psi(ix)\right] - \tfrac{1}{2}\ln\left(x^2\right)$$



J. Carbonell et al., PLB 397 (1997) 345
A. Zenoni et al., PLB 461 (1999) 405

CERN AD (Antiproton Decelerator)

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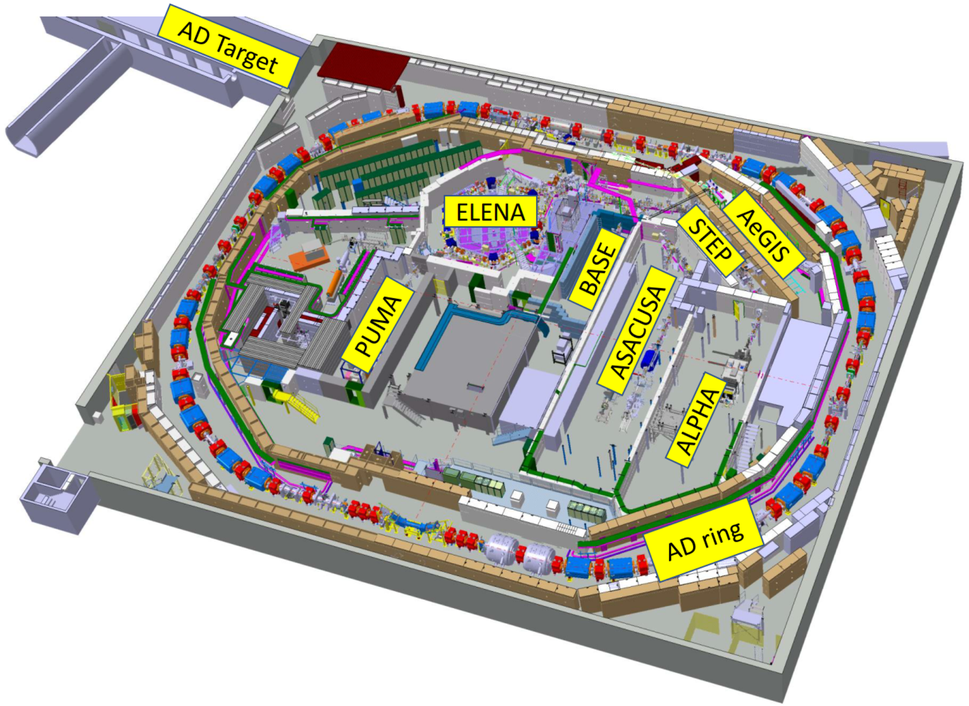

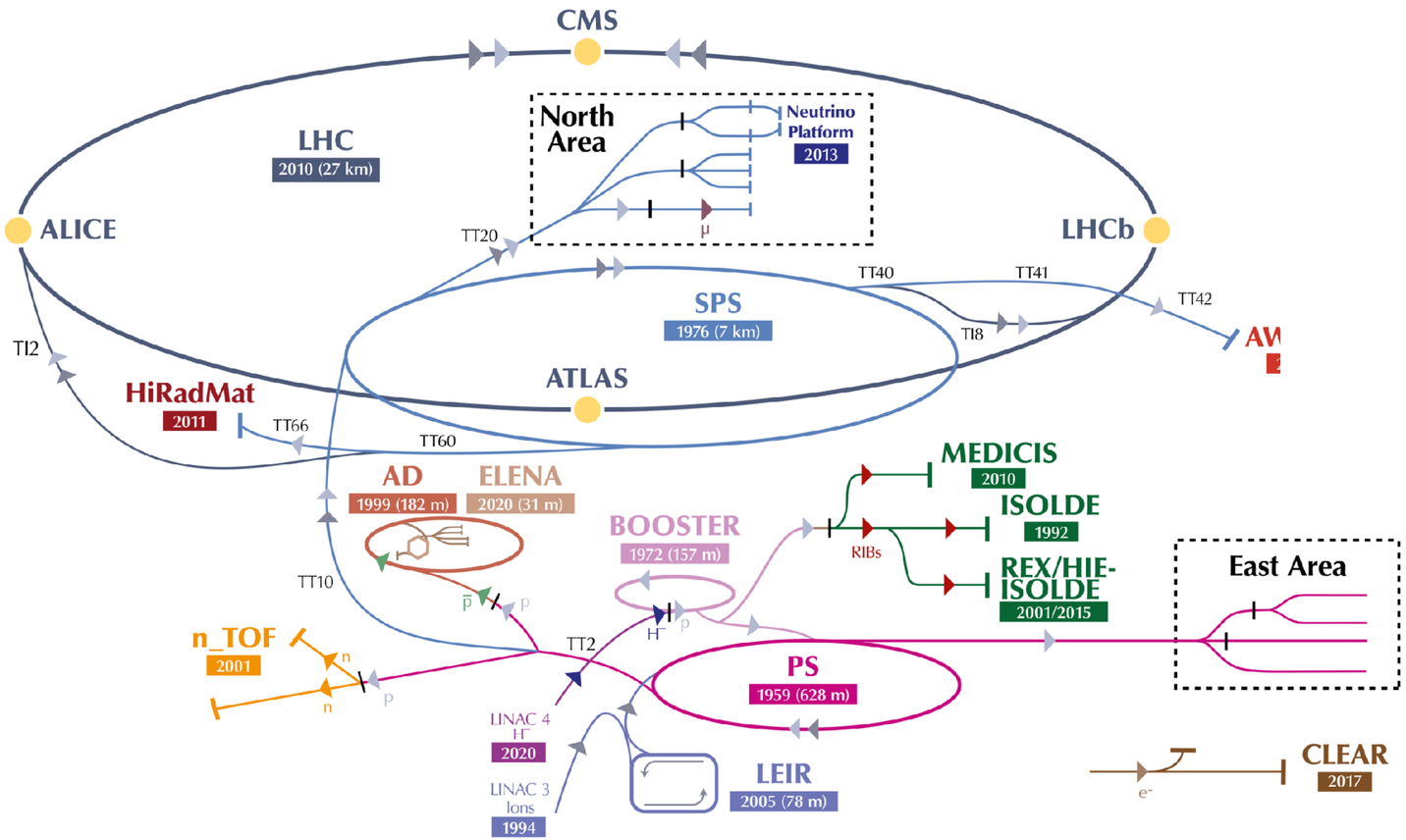

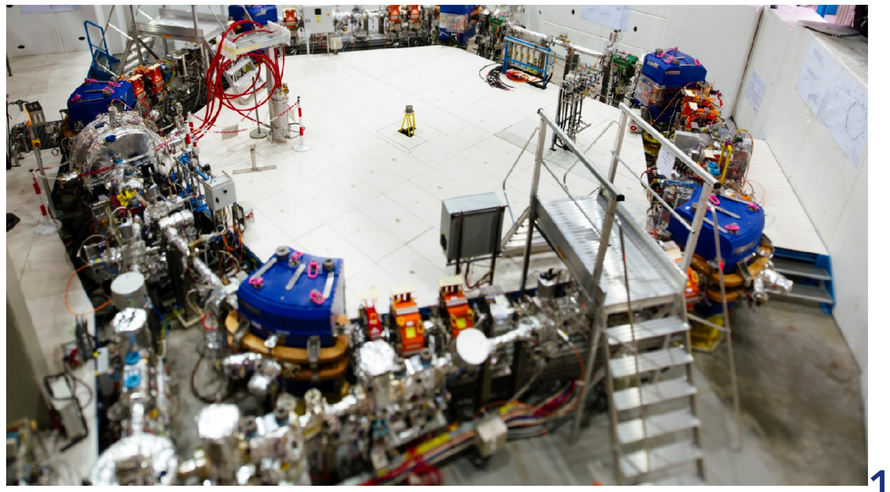

Novel concept: low-energy antineutron production

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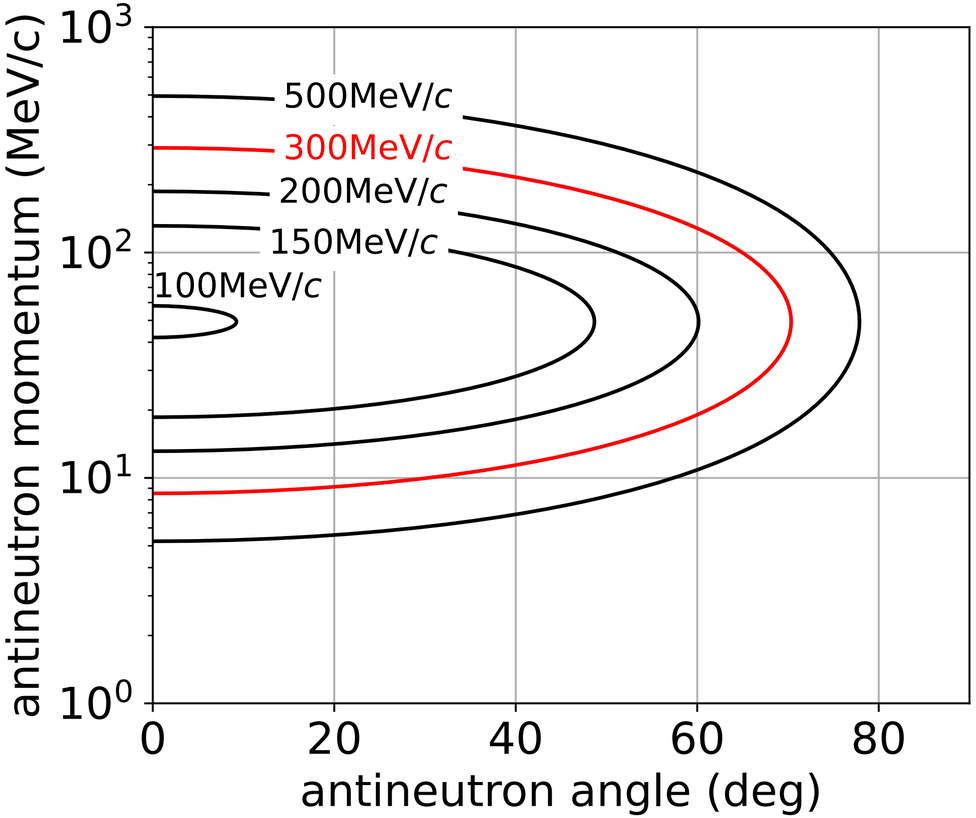
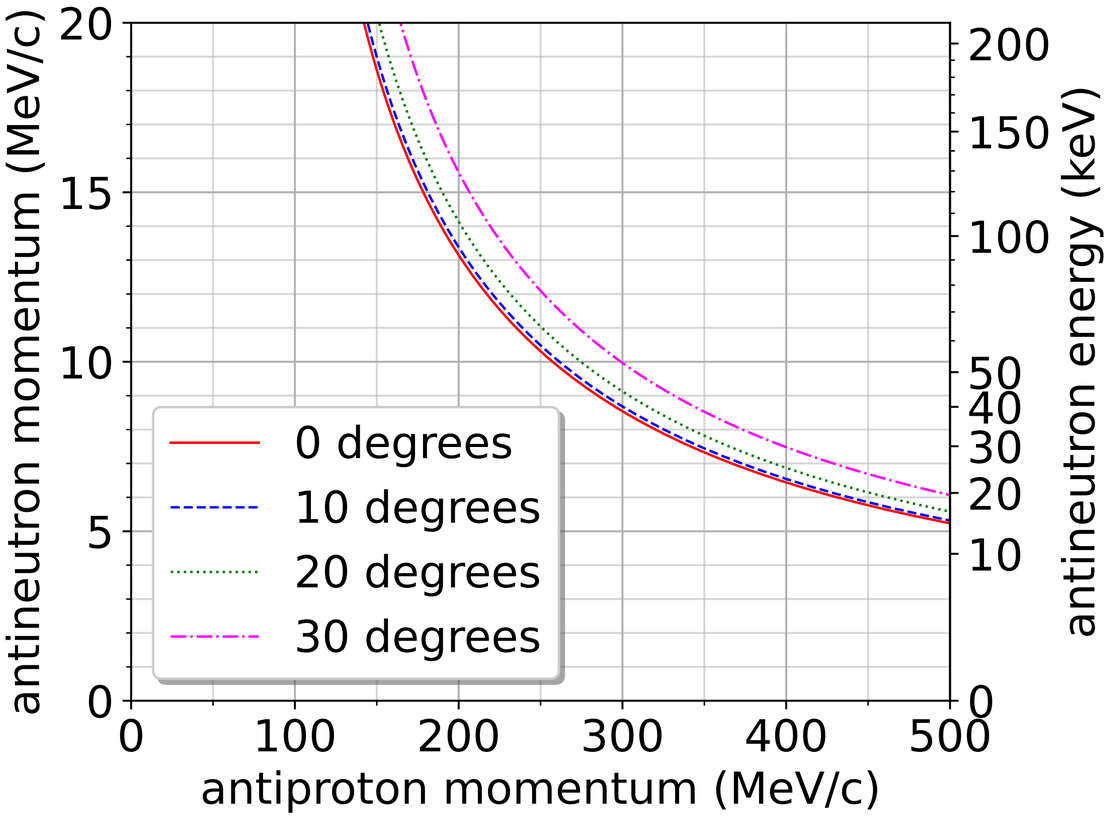
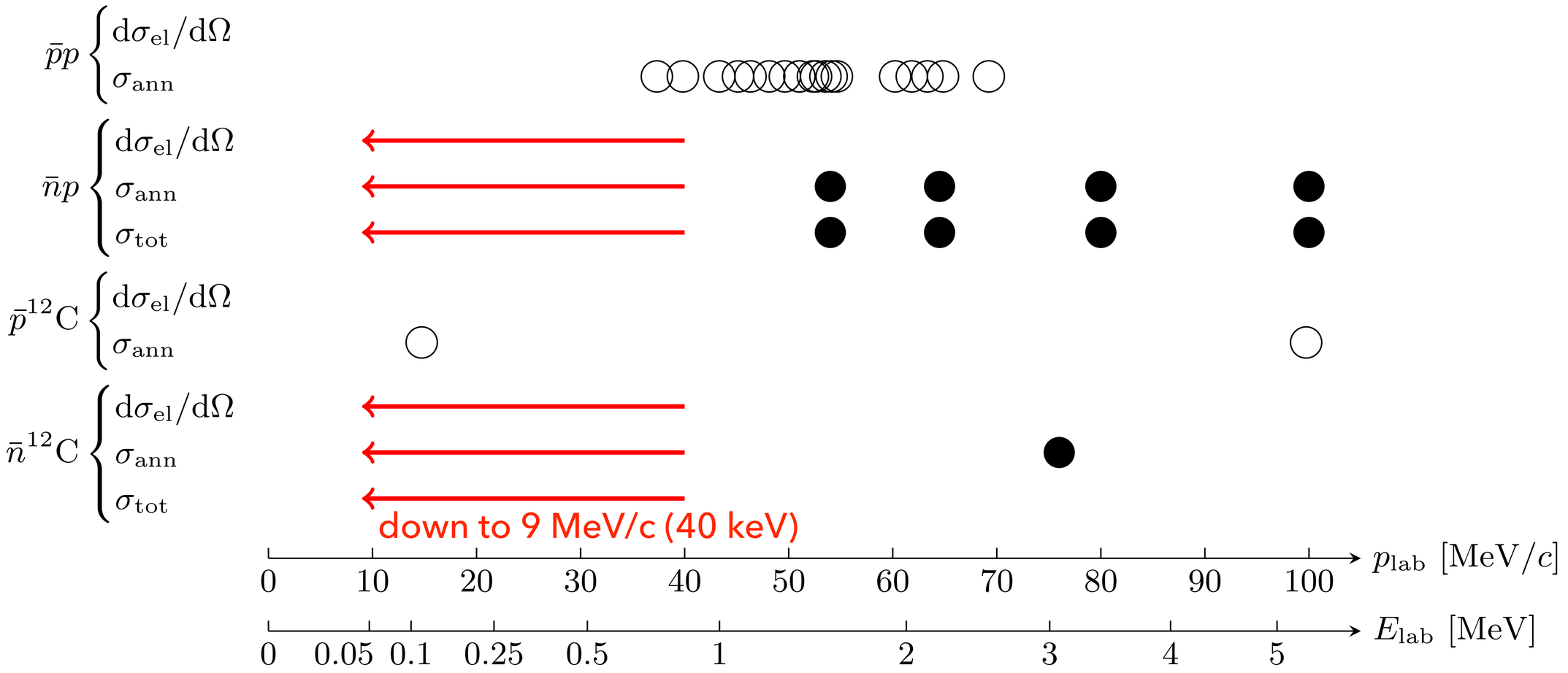
arXiv:2503.06972

- 300 MeV/c antiprotons from CERN-AD (Antiproton Decelerator)
- $p_{\mathrm{lab}} = 9\,\mathrm{MeV}/c$ (40 keV) antineutrons can be backward-produced in charge-exchange reaction ($p\bar{p} \rightarrow n\bar{n}$)
- 1.0 antineutrons per cycle (~2min.) → scattering experiments feasible





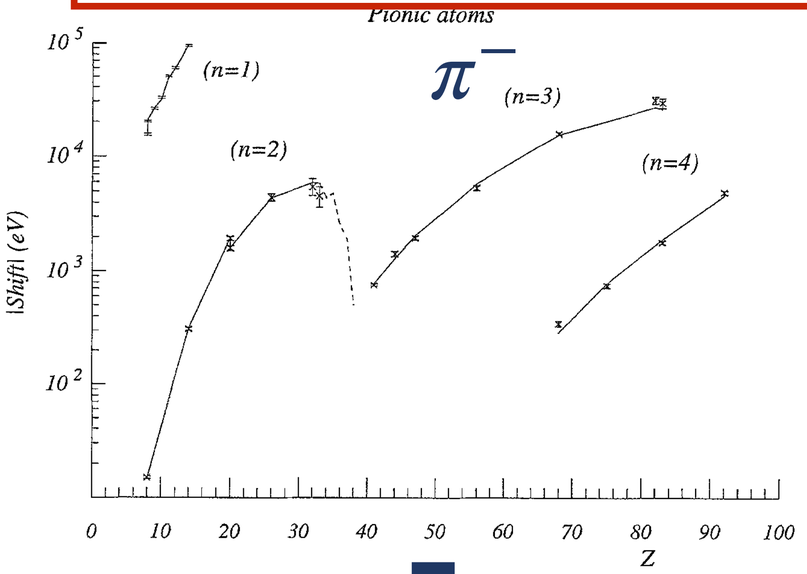
Summary of existing data and prospect

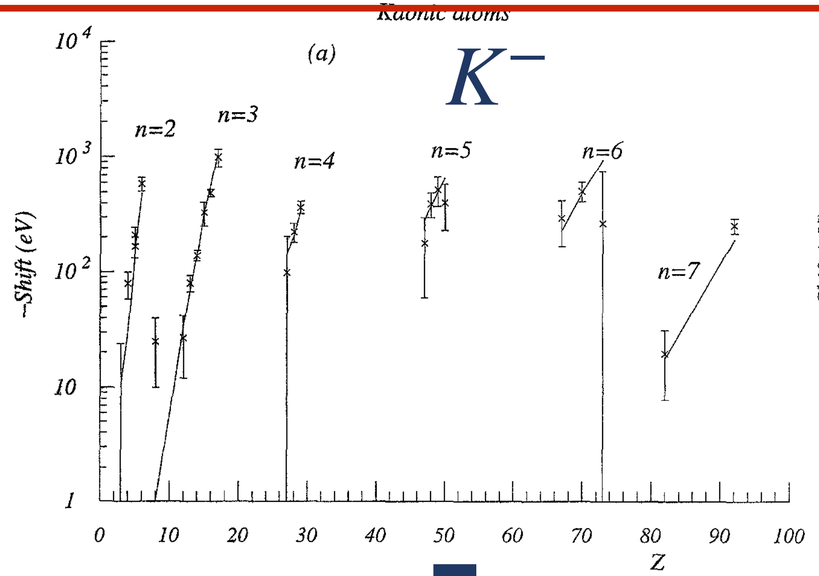


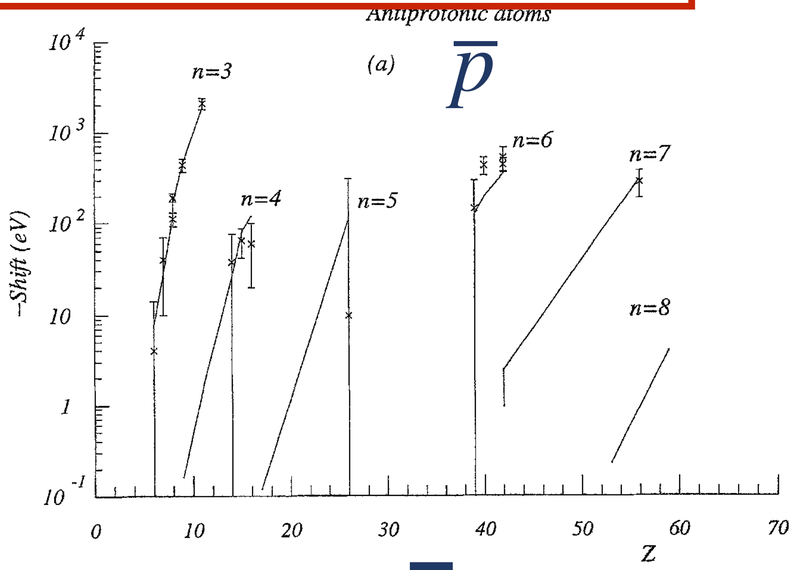
Strong interaction in exotic atoms

C.J. Batty et al., Phys. Rep. 287 (1997) 385

shift (= $E_{\mathrm{measured}} - E_{\mathrm{Coulomb}}$), width of atomic levels → strong interaction between hadron and nucleus







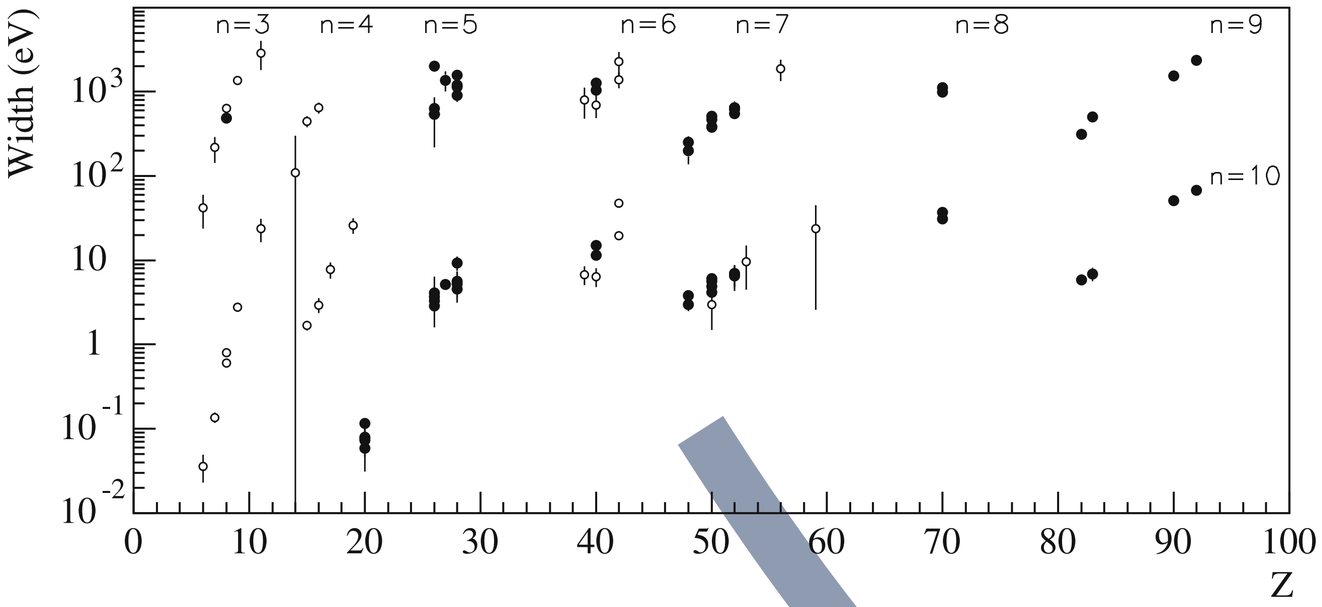
- **pionic hydrogen/deuterium**
- **deeply bound pionic atoms**

- **kaonic hydrogen/deuterium**
- **kaonic helium-3/4**

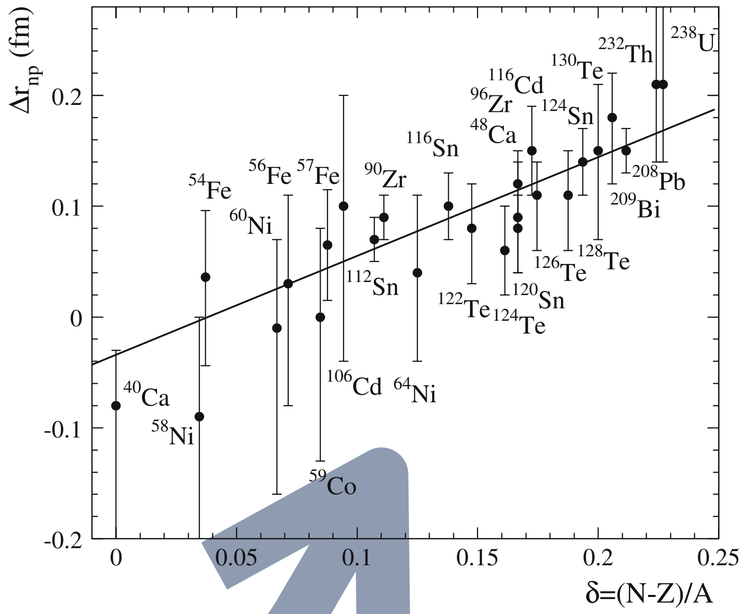
- **protonium**
- **anti-protonic deuterium**
- **CERN PS209 (^{16}O, …, ^{238}U)**

CERN PS209 (investigation of nuclear periphery)

A. Trzcińska et al., Hyperfine Interact. 194 (2009) 271



$$\Delta r_{\mathrm{np}} = \langle r^2 \rangle_{\mathrm{n}}^{1/2} - \langle r^2 \rangle_{\mathrm{p}}^{1/2}$$



optical potential

$$2\mu U_{\mathrm{opt}}(r) = -4\pi\left(1+\frac{\mu}{m}\right)(b_0\rho(r) + \cancel{b_1\delta\rho(r)})$$

$$\rho(r) = \rho_n(r) + \rho_p(r)$$

$$\delta\rho(r) = \rho_n(r) - \rho_p(r)$$

$b_0 = 2.5 + 3.4i$ (global fit)

C.J. Batty et al., Nucl. Phys. A 592 (1995) 487

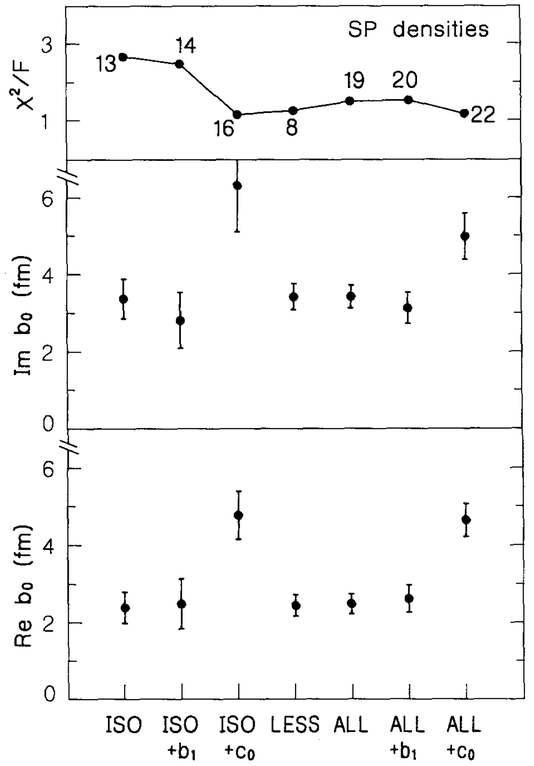
$$\rho_{\mathrm{n/p}}(r) = \frac{\rho_0}{1+\exp[(r-c_{\mathrm{n/p}})/a_{\mathrm{n/p}}]}$$

with $c_{\mathrm{n}} = c_{\mathrm{p}}$

Revisiting the isovector term

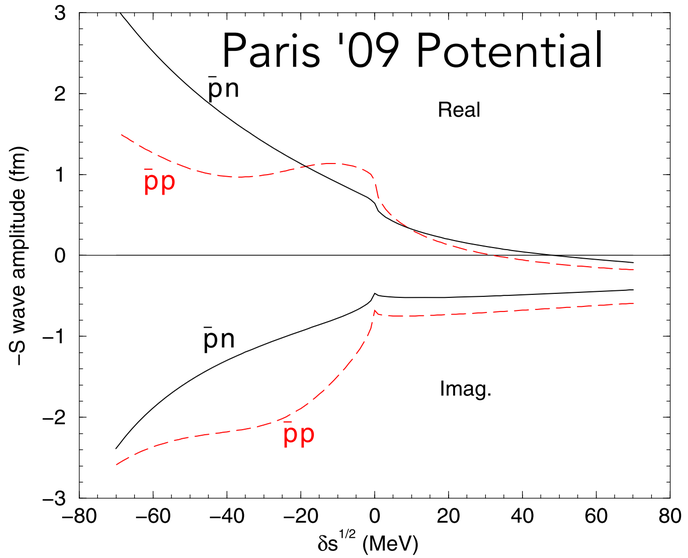
$$2\mu U_{\mathrm{opt}}(r) = -4\pi\left(1+\frac{\mu}{m}\right)(b_0\rho(r)+\cancel{b_1\delta\rho(r)})$$

- Inclusion of the isovector (b_1) term did not improve the χ^2/ndf in the global fit.
- Many literatures ignores the isovector term.
- Levels are sensitive only to extremely outer, low density ($< 0.1\rho_0$) regions, where neutrons dominate over protons.

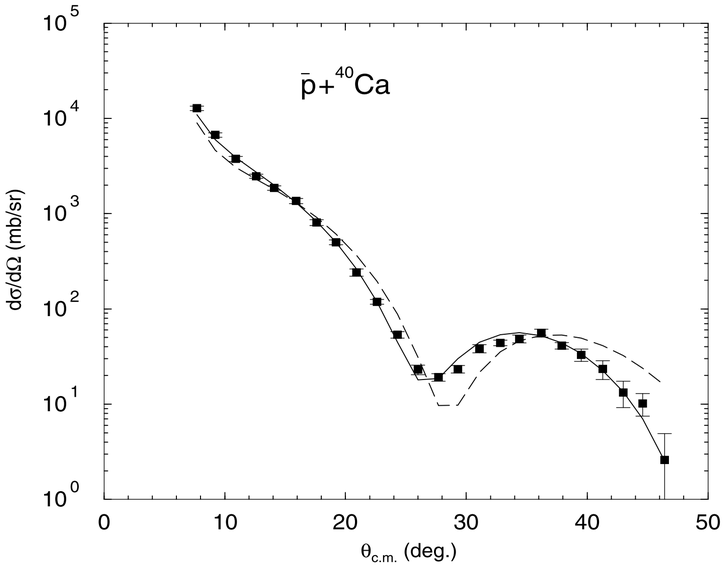


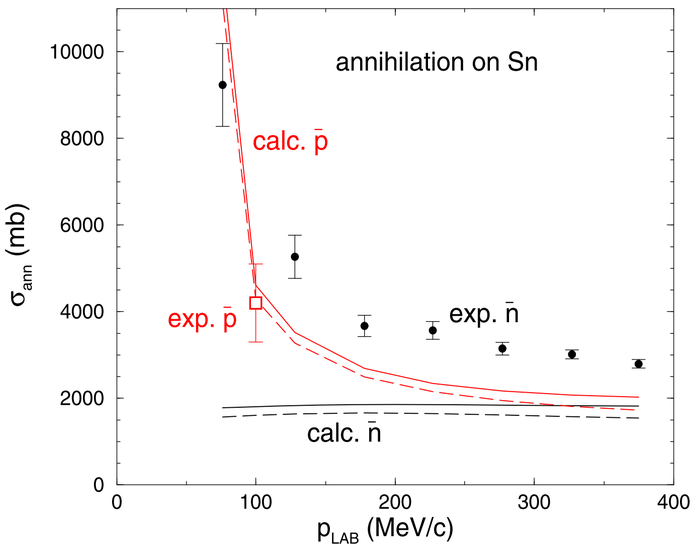
C.J. Batty et al., Nucl. Phys. A 592 (1995) 487
see also
E. Friedman and A. Gal, NIM B 214 (2004) 160
E. Friedman et al., Nucl. Phys. A 761 (2005) 283

Open questions about $\bar{N}A$ interactions



Does b_1 happen to be consistent with zero, even if $\bar{\mathrm{p}}\mathrm{p}$ and $\bar{\mathrm{p}}\mathrm{n}$ interactions are different?





$\bar{\mathrm{n}}A$ annihilation cannot be described by the optical potential determined by a global fit for antiprotonic atoms.

E. Friedman et al., Nucl. Phys. A 943 (2015) 101

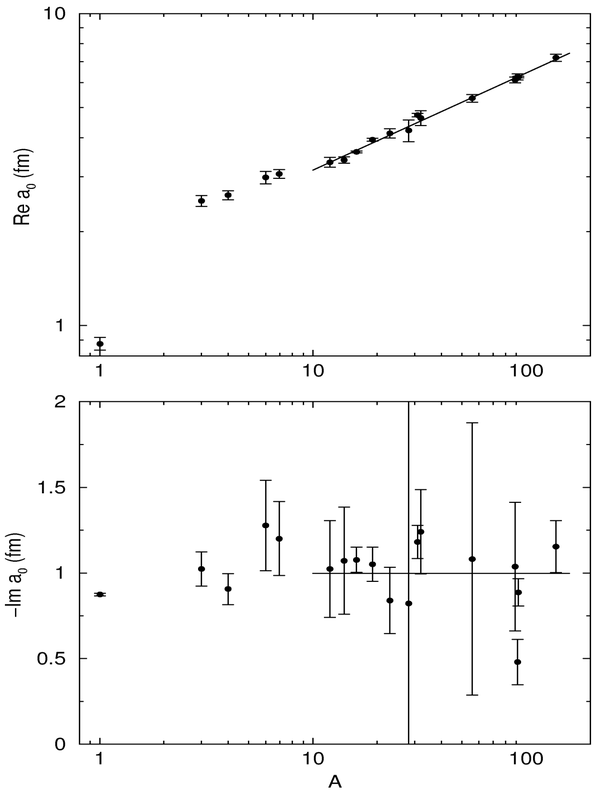
Antineutron-nucleus scattering lengths

- Indirectly determined by solving a Schrödinger eq. with the optical potential,
  which reproduces energy levels of antiprotonic atoms

$$2\mu U_{\mathrm{opt}}(r) = -4\pi\left(1+\frac{\mu}{m}\right) b_0 \rho(r)$$

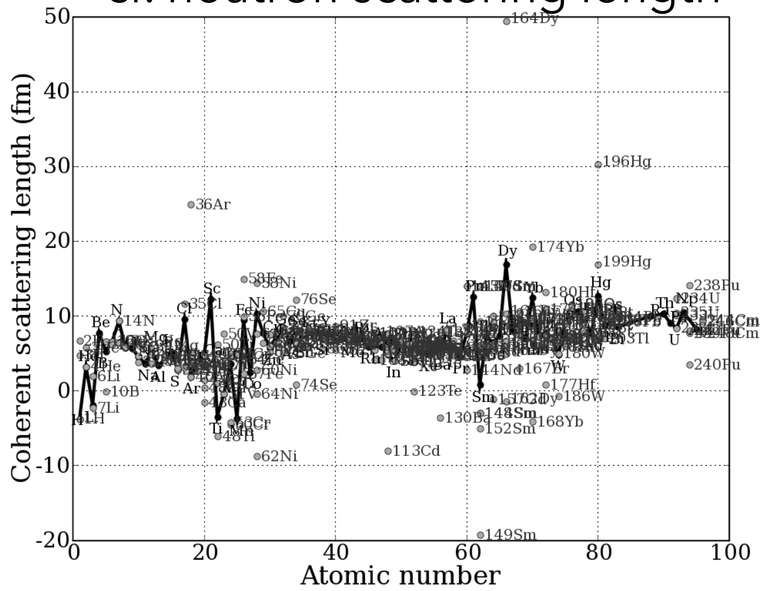
- $\mathrm{Re}\, a_0 = (1.54 \pm 0.03) A^{0.311\pm0.005}\ \mathrm{fm}$
- $\mathrm{Im}\, a_0 = -(1.00 \pm 0.04)\ \mathrm{fm}$

- Absence of low-energy scattering measurement



Batty et al., Nucl. Phys. A 689 (2001) 721

cf. neutron scattering length



GISAXS Community Website

Correlation between $a_{\bar{n}A}$ and optical potential

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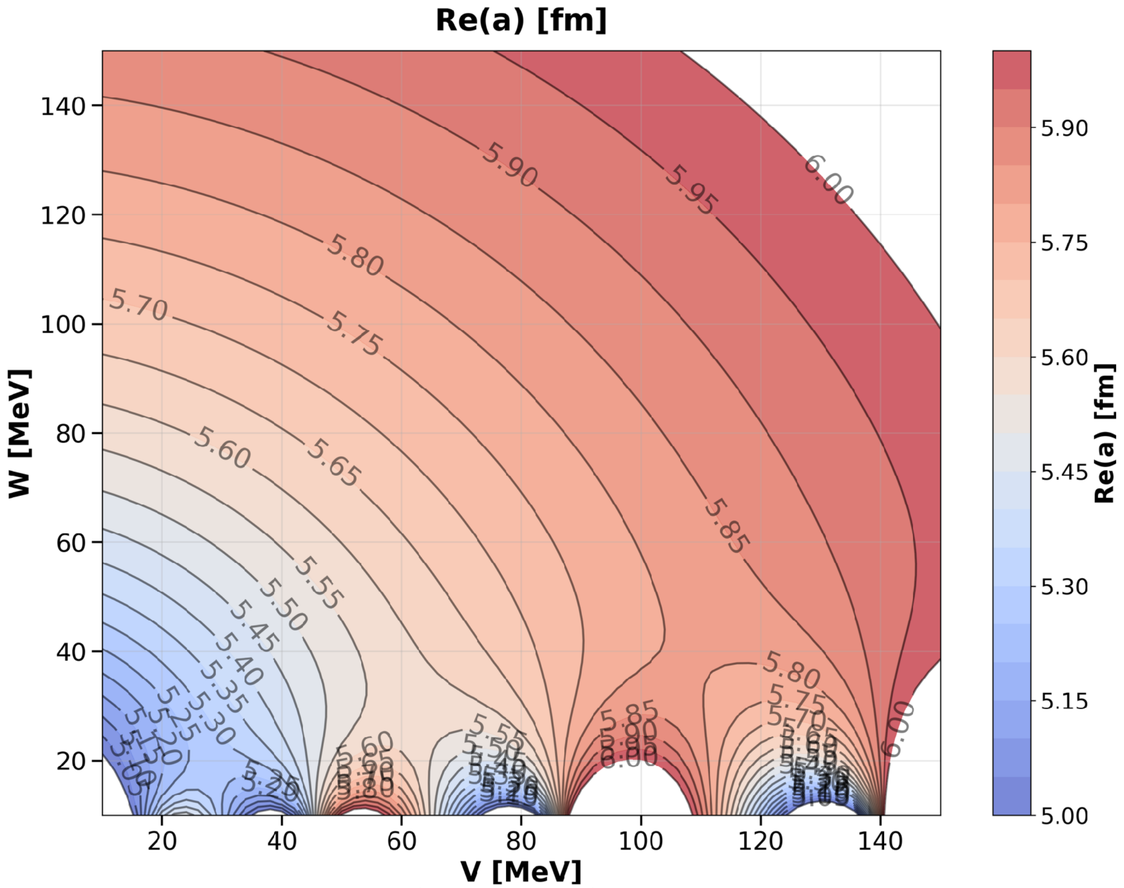
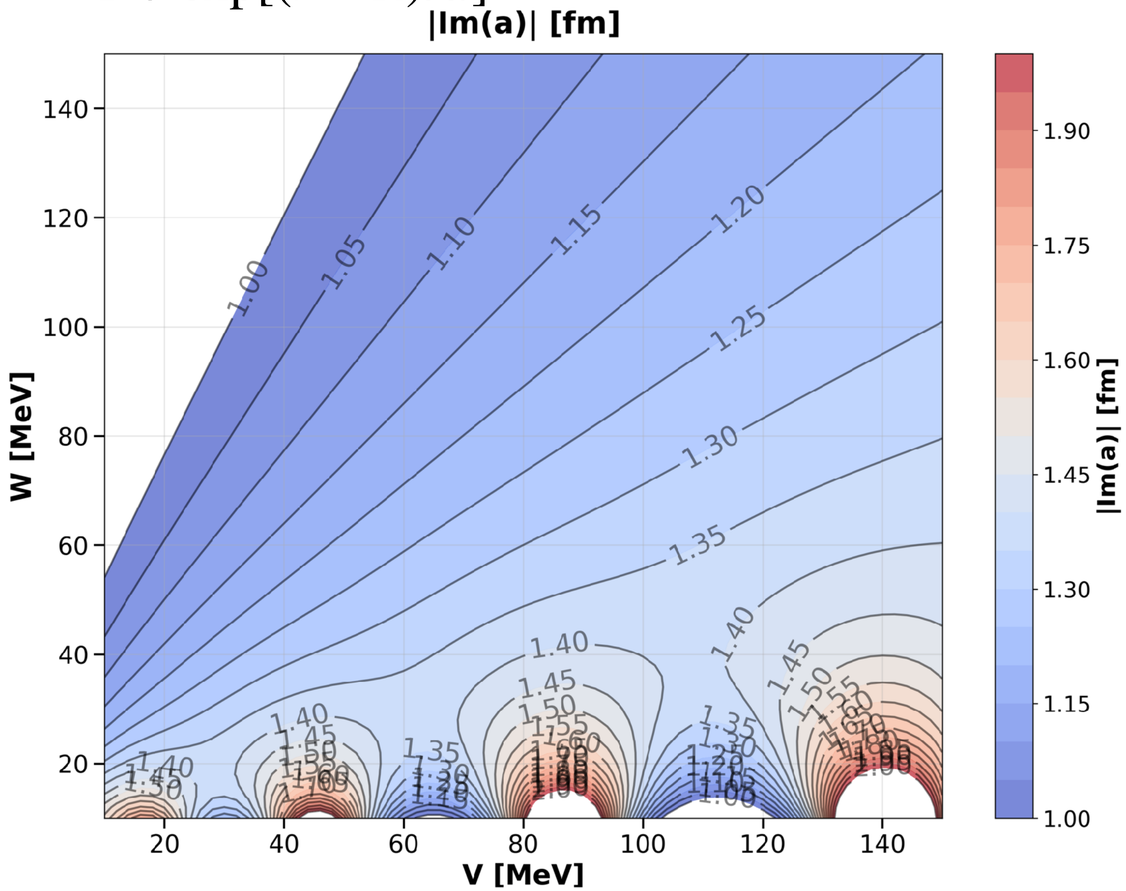
Woods-Saxon type optical potential: $V(r) = -\dfrac{V + iW}{1 + \exp[(r - R)/a]}$ (R=5fm, a=0.5fm)





cf. $V(r) = -\dfrac{2\pi}{\mu}\left(1 + \dfrac{\mu}{m_N}\right) b_0 \rho(r)$

for a square-well potential with $W \to -\infty$,
$\mathrm{Re}\, a \to R$ (radius) and $\mathrm{Im}\, a \to 0$

→ V~103MeV and W=158 MeV for $b_0 = 1.3 + 1.8i$ fm (Batty et al., Nucl. Phys. A 761, 283 (2005))

Neutron–antineutron oscillation

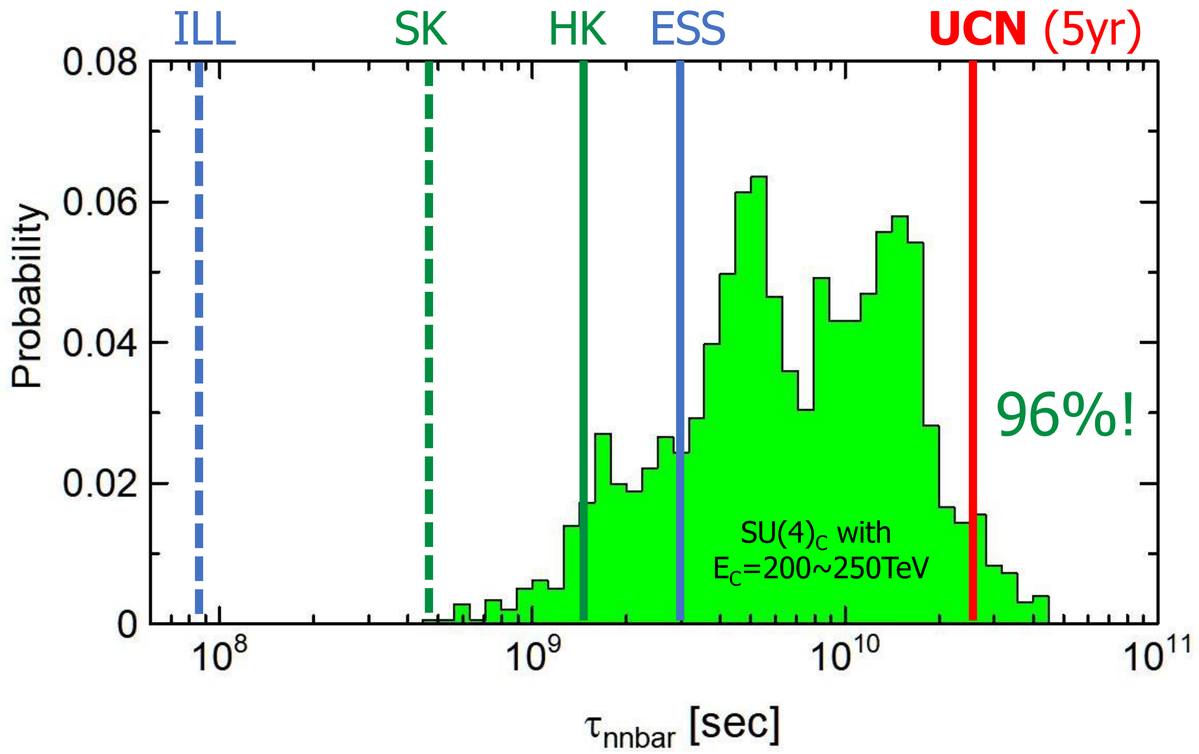
- violates both B and B-L (B: baryon number, L: lepton number)
- test of Grand Unified Theory

- Lower limit on oscillation time
  - ILL (1994) free neutron

    $\tau_{n\bar{n}} > 8.6 \times 10^7\ \mathrm{s}$
  - Super-Kamiokande (2021) bound *n*

    $\tau_{n\bar{n}} > 4.7 \times 10^8\ \mathrm{s}$

M. Baldo-Ceolin et al., Z. Phys. C 63, 409 (1994).
K. Abe et al., Phys. Rev. D 103, 012008 (2021).

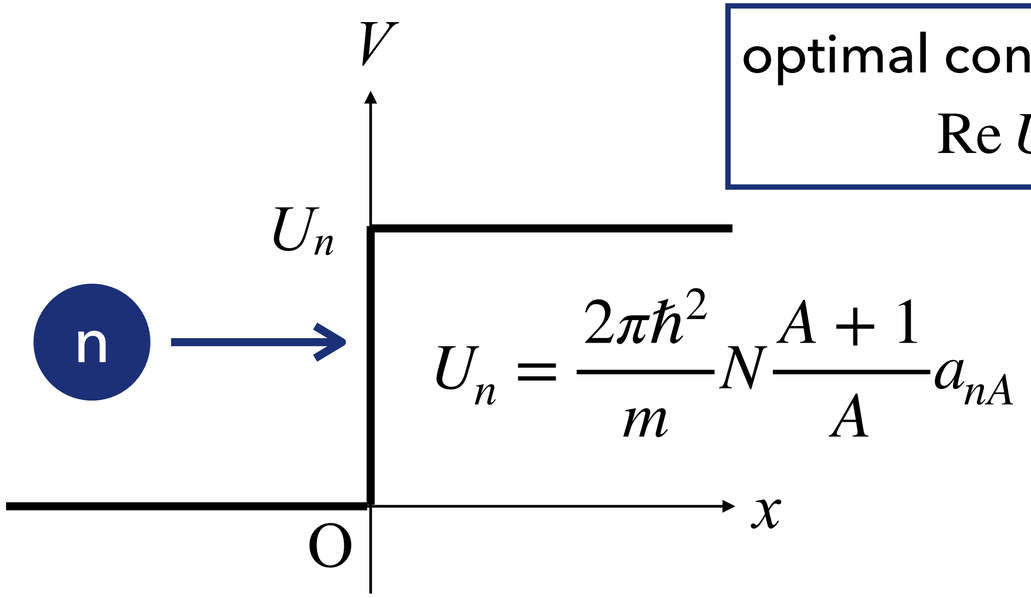


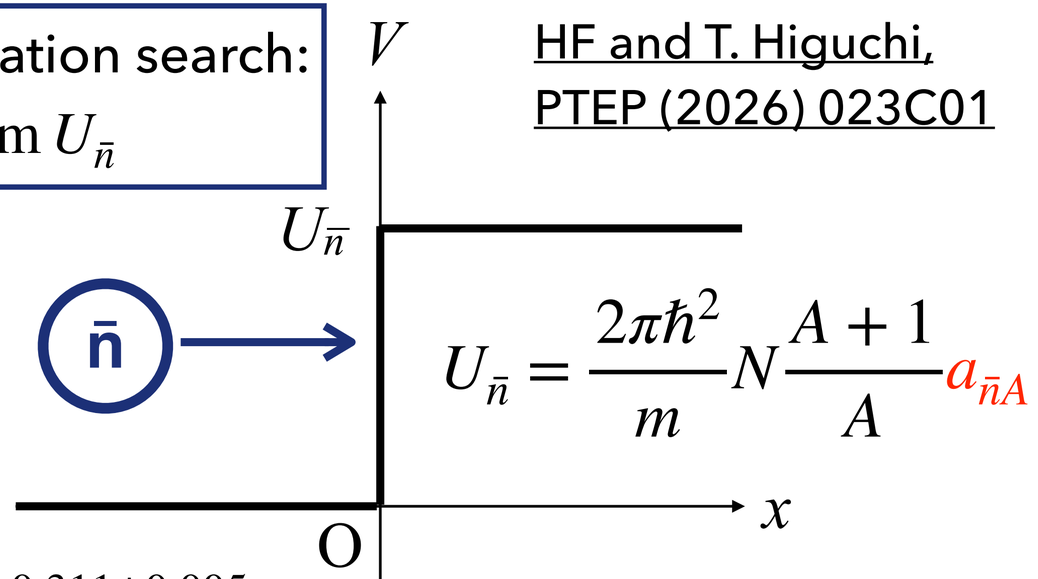
D.G. Phillips II et al., Phys. Rep. 612 (2015) 1
K.S. Babu et al., Phys. Rev. D 87 (2013) 115019
T. Shima, Symmetry 17 (2025) 1524

Why is the scattering length important?

optimal condition for n–n̄ oscillation search:
$\mathrm{Re}\, U_{\bar{n}} \approx U_n$ and small $\mathrm{Im}\, U_{\bar{n}}$

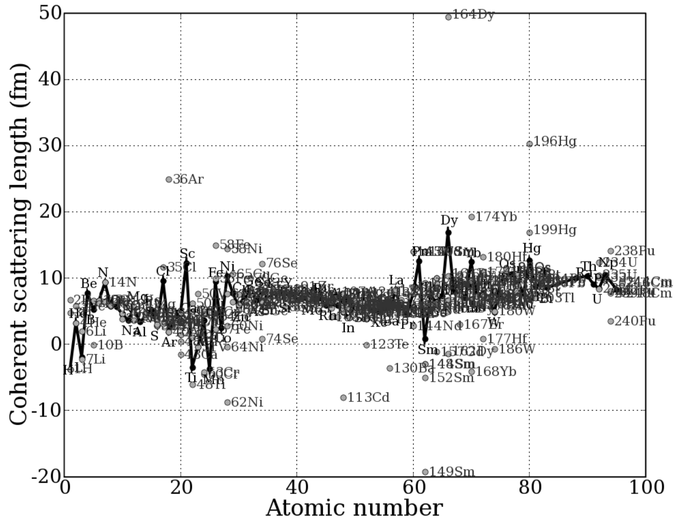
HF and T. Higuchi,
PTEP (2026) 023C01





$a_{\bar{n}A} = (1.54 \pm 0.03) A^{0.311 \pm 0.005} - i(1.00 \pm 0.04)$ fm

evaluated using p̄-nucleus optical potentials,
which reproduces X-ray energies of antiprotonic atoms



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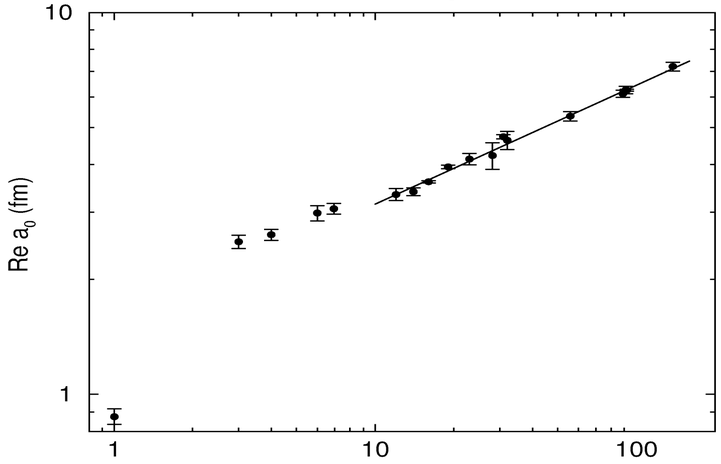
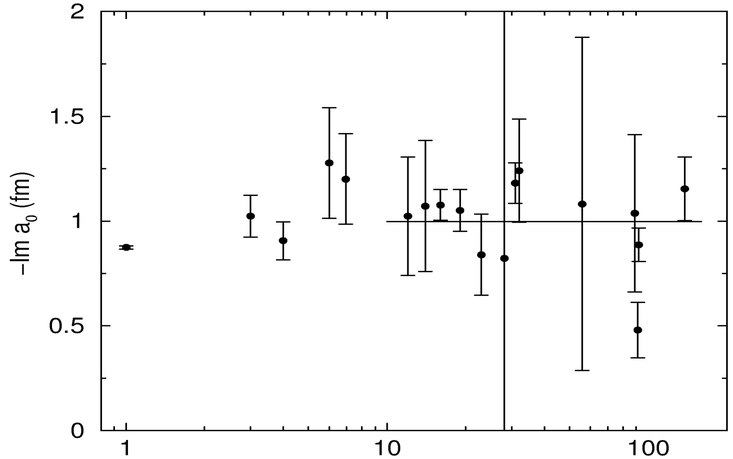
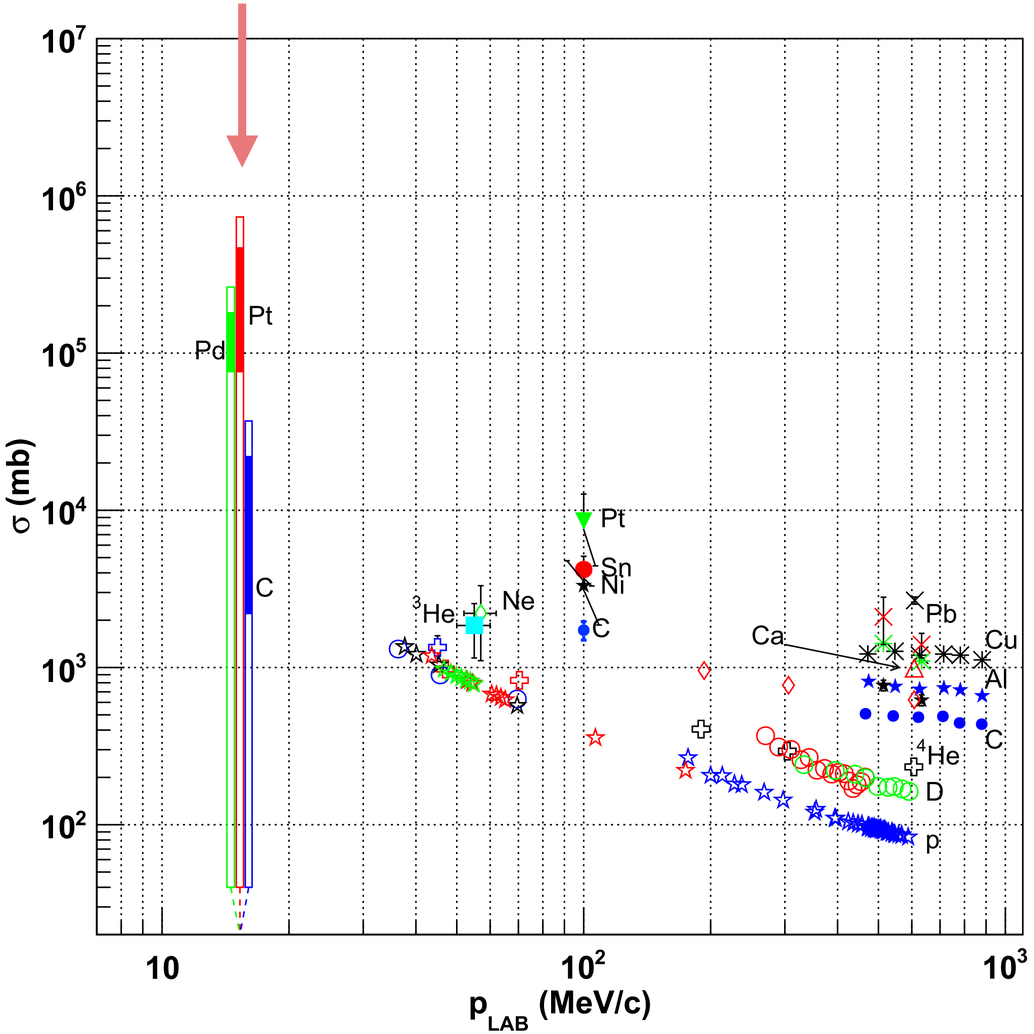




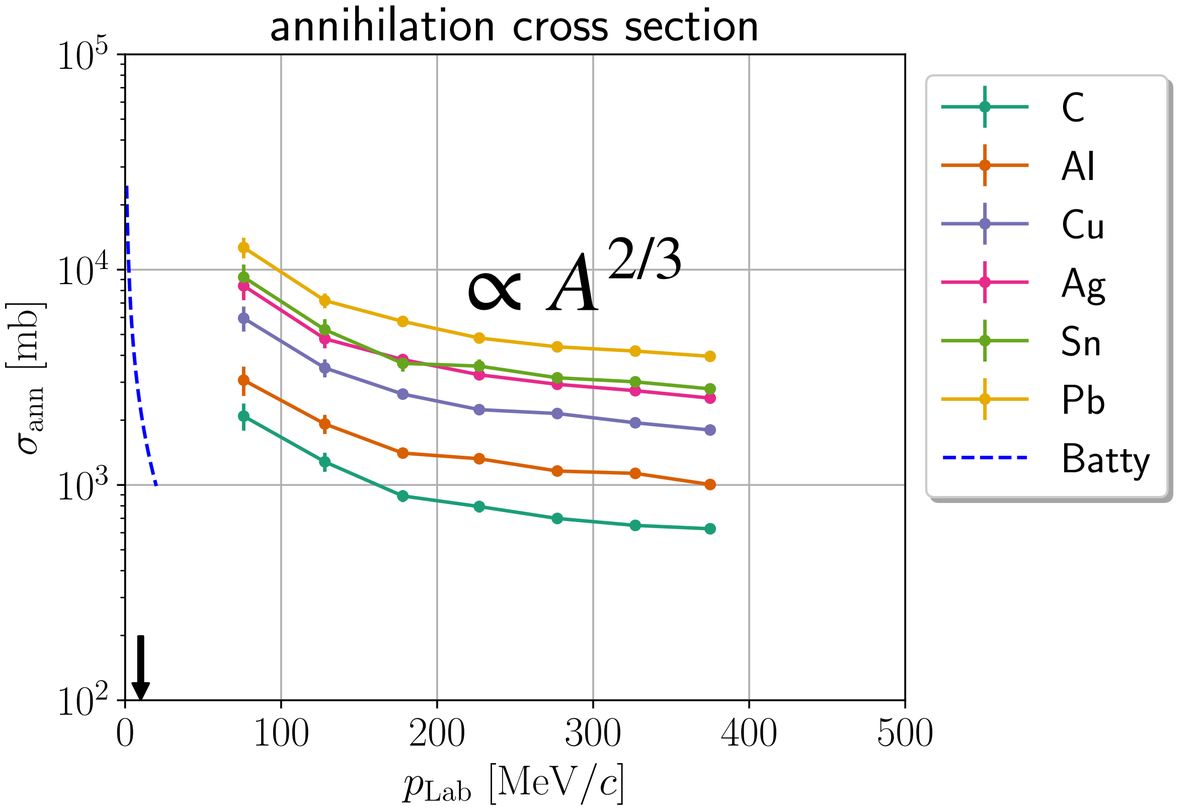
Batty et al., Nucl. Phys. A 689 (2001) 721

p̄A annihilation cross sections

(Coulomb-corrected) scattering length? [$\ell = R \cdot p < \hbar/2$]



Aghai-Khozani et al. (ASACUSA), NPA 1009 (2021) 122170



M. Astrua et al., NPA 697 (2002) 209

Summary of existing data and prospect

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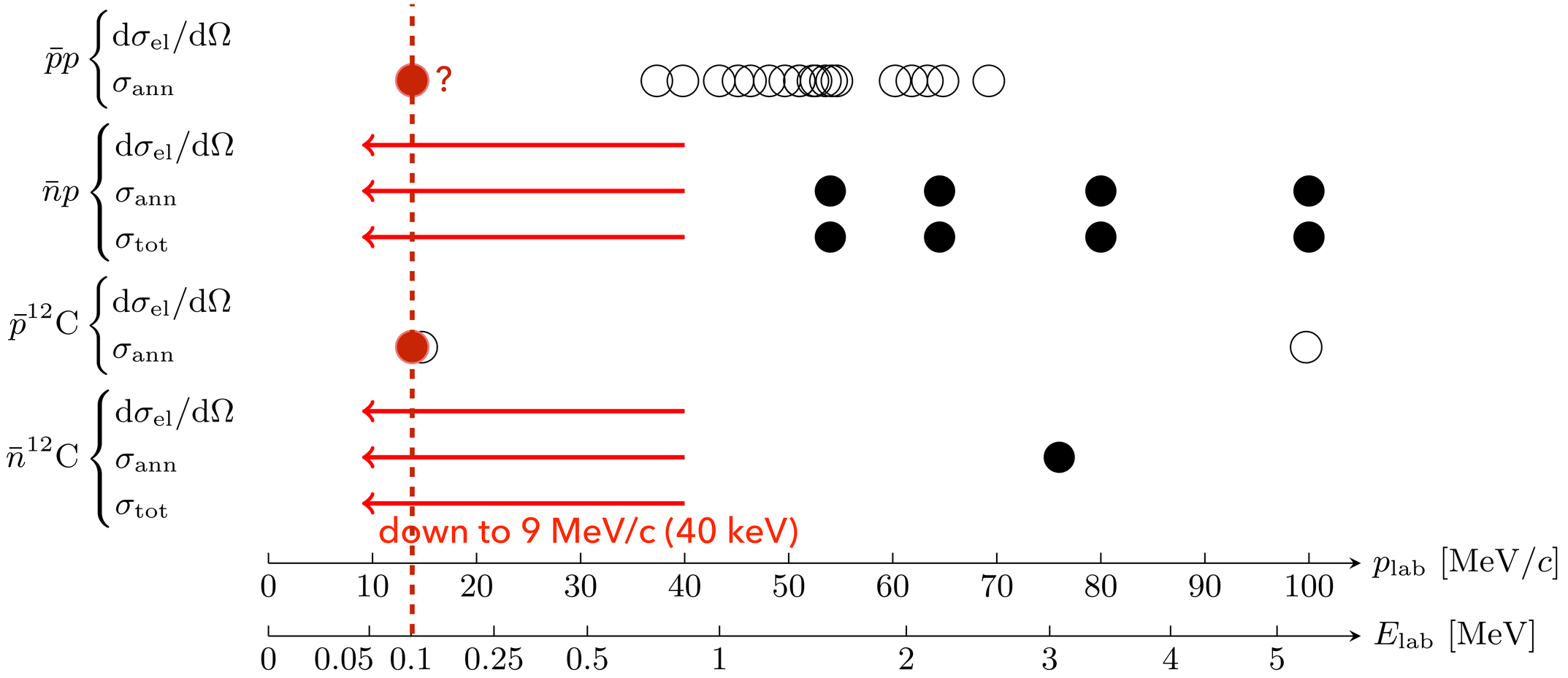
100 keV antiprotons from ELENA



まとめ

- 様々なN$\bar{\text{N}}$ポテンシャルが提案されているが、それぞれ大きく異なる。
- 一部例外を除き、低エネルギー散乱断面積は採用されず。
- s波散乱断面積を用いてs波散乱長をモデル非依存に決定したい。

- 反陽子原子を再現する反陽子–原子核光学ポテンシャルは、反核子–原子核の散乱断面積をあまりよく再現しない
- アイソスピン依存性を無視した $t\rho$ 近似が原因？エネルギー依存性？

- 同じくs波散乱断面積からs波散乱長をモデル非依存に決定したい。
- s波散乱長 → 中性子–反中性子振動探索においても重要なパラメータ