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Institut für Theoretische Physik

In-Medium Dynamics of ω-Mesons

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NUMEN STRONG-2020 panda NUSTAR

ω-Mesons in Free Space

$$J^{PC}\ (I^G) = 1^{--}\ (0^-)\ .$$

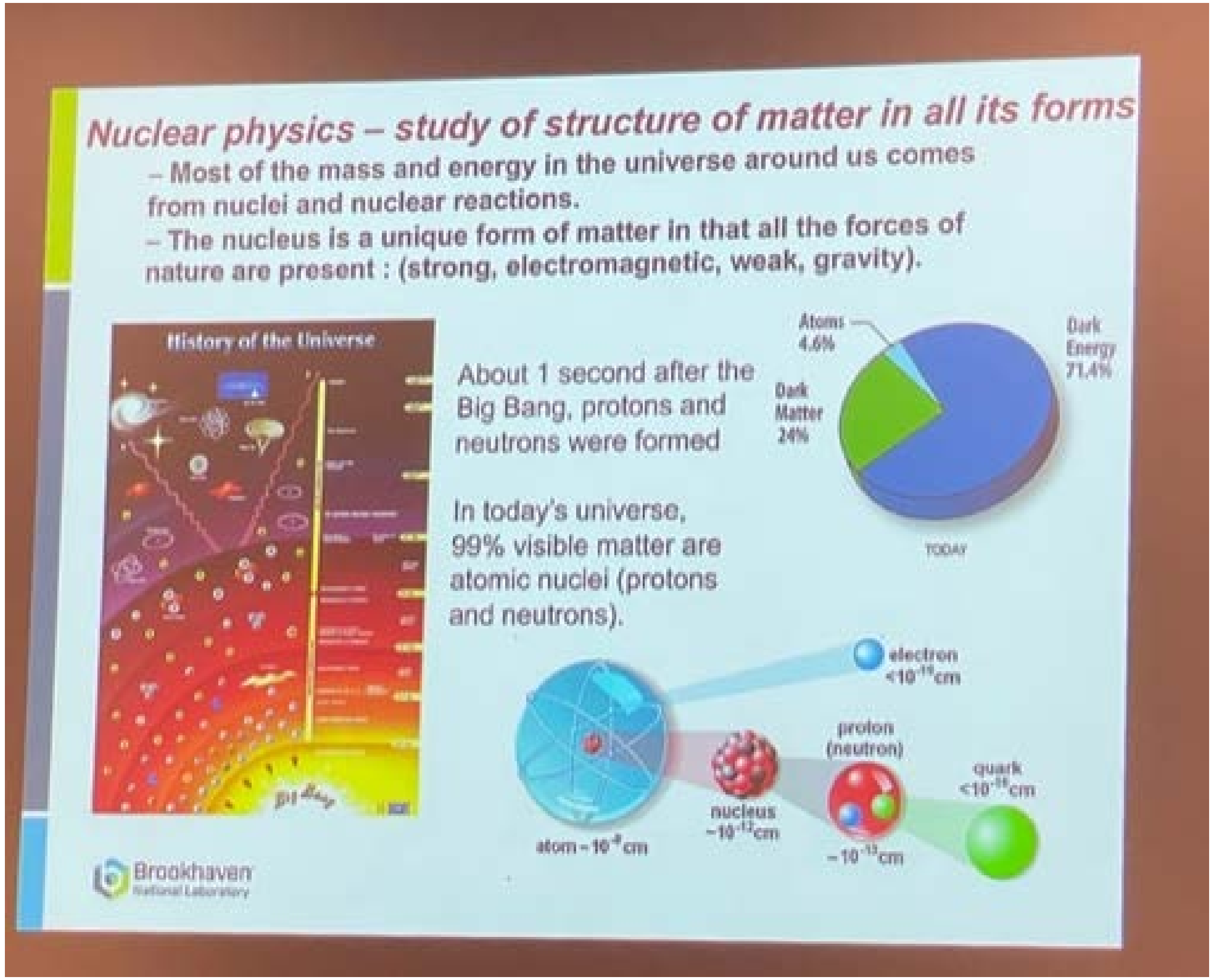
$m_\omega = (781.94 \pm 0.12)$ MeV $\qquad \Gamma_0 = (8.41 \pm 0.09)$ MeV

$\omega \to \pi^0\pi^+\pi^-$ and $\omega \to \rho\pi$

ω -->	Γ_i/Γ_0 in %	Γ_i in MeV
$\pi^0\pi^+\pi^-$	88.8 ± 0.7	7.486
$\pi^0\gamma$	8.5 ± 0.5	0.717
$\pi^+\pi^-$	2.21 ± 0.3	0.186
$\eta\gamma$	$(6.5 \pm 1.0)\cdot 10^{-4}$	$5.47 \cdot 10^{-3}$
$\pi^0 e^+ e^-$	$(5.9 \pm 1.9)\cdot 10^{-4}$	$5.0 \cdot 10^{-3}$
$\pi^0 \mu^+ \mu^-$	$(9.6 \pm 2.3)\cdot 10^{-5}$	$8.0 \cdot 10^{-4}$
$e^+ e^-$	$(7.07 \pm 0.19)\cdot 10^{-5}$	$5.9 \cdot 10^{-4}$

G-parity forbidden, ω↔ρ mixing

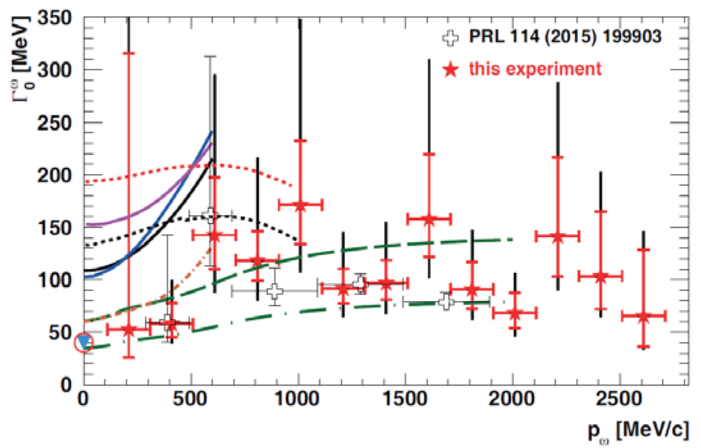
Why exposing Mesons to Nuclear Matter?



c/o Haiyan Gao

Agenda

- Mesons in a Nuclear Environment
- Lagrangian for ωNN and ωNN* Interactions
- N^*N^{-1} particle-hole Polarization Modes
- ω-Mesons in Infinite Nuclear Matter
- ω-Mesons in a ^{93}Nb Nucleus
- $\omega + {}^{93}$Nb Bound States
- Outlook



CBELSA/TAPS Data:
Friedrich et al., Eur. Phys. J. A (2016) 52: 297

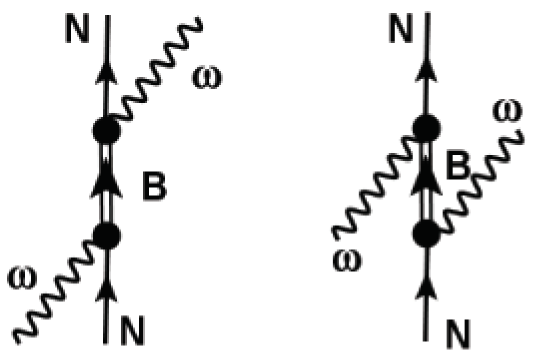
W. Peters, H.L. et al.
The spectral function of the rho meson in nuclear matter
Nucl. Phys. A 632 (1998) 109

H.L.
Interactions of ω Mesons in Nuclear Matter and with Nuclei
Eur. Phys. J A (in print)

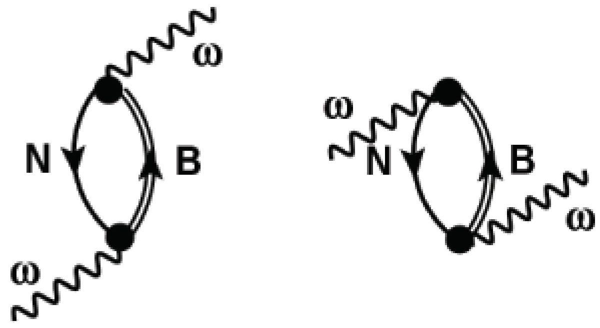
Polarization Tensors and Self-Energies

ω-Mesons interacting with Nuclear Matter: The Leading Order Processes

$$\approx O(g^2_{\omega NB})$$



$$T_{\omega N} = V_{\omega N} + V_{\omega N} G_{\omega N} T_{\omega N}$$



$$\Pi^{\mu\nu}_{\alpha\beta} = -tr_A \langle A | \widehat{\Gamma}^{\mu}_{\beta} \mathcal{G}_A \widehat{\Gamma}^{\nu}_{\alpha} | A \rangle$$

The ω-nucleon scattering amplitudes (left) and the corresponding particle{hole type diagrams (right). Nucleons and hole states are denoted by N. The intermediate B = N,N* states (left), which become particle states (right), are indicated by double line

NN^{-1} and N^*N^{-1} Polarization Tensors and Self-Energies in Infinite Matter (B=N,N*)

$$\Pi^{\mu\nu}_{NB}(w,\mathbf{q}) = \int \frac{d^3k}{(2\pi)^3} \frac{\theta(k^2_{F_N}-\mathbf{k}^2)\theta((\mathbf{k}+\mathbf{q})^2-k^2_{F_B})}{2E^*_N(\mathbf{k})} Tr_s(\Gamma^\mu(\not{k}^*+M^*_N)\Gamma^\nu G_B(\mathbf{k}+\mathbf{q}|k_F))$$

Interaction Vertices

$\Gamma^\mu_{NB} = \gamma^\mu$ if B=N,N* is a positive parity state,

$\Gamma^\mu_{NB} = \gamma_5\gamma^\mu$ if B=N* is a negative parity state,

Omega In-Medium Self-Energy Tensor

$$S^{\mu\nu}_{\omega A}(w,\mathbf{q}) = \sum_{N;B} g^2_{\omega NB}\Pi^{\mu\nu}_{NB}(w,\mathbf{q}),$$

Longitudinal and Transversal In-Medium Self-Energies

$$\mathcal{S}^{\mu\nu}(w, \mathbf{q}) = (P_L^{\mu\nu} + P_T^{\mu\nu})^2 \mathcal{S}^{\mu\nu}(w, \mathbf{q}) = P_L^{\mu\nu} \Sigma_L(w, \mathbf{q}) + P_T^{\mu\nu} \Sigma_T(w, \mathbf{q})$$

$$\Sigma_{L/T}(w, \mathbf{q}) = P_{L/T}^{\mu\nu} \mathcal{S}_{\mu\nu}(w, \mathbf{q}) = \sum_{N=p,n;B} g_{BN\omega}^2 P_{L/T}^{(NB)}(w, \mathbf{q}).$$

$$P_{L/T}^{(NB)}(w, \mathbf{q}) = P_{L/T}^{\mu\nu} \Pi_{\mu\nu,NB}(w, \mathbf{q}).$$

ω-Meson Interactions on ^{93}Nb

Choice of States and Methods

- NN^{-1} and N^*N^{-1} with P-wave (positive parity) and S-wave (negative parity) resonances, $M_{N^*} < 2.5$ GeV
- Only isospin I=½ resonances are allowed
- g_{N^*Nw} coupling constants are determined by fit to data

Particle	Mass/MeV	total Width/MeV	$g_{N^*N\omega}$	M^*/M
ω	782.7	8.68	–	1
$P_{11}(940)$	938.92	–	2.076	0.60
$P_{11}(1440)$	1386	350	0.218	0.72
$P_{11}(1710)$	1670	140	2.163	0.78
$P_{11}(1880)$	1880	230	$< 10^{-3}$	0.80
$P_{11}(2100)$	2100	260	$< 10^{-3}$	0.82
$P_{11}(2300)$	2300	340	1.714	0.84
$P_{13}(1720)$	1720	225	0.022	0.78
$P_{13}(1920)$	1920	215	0.017	0.80
$S_{11}(1535)$	1535	150	$< 10^{-3}$	0.76
$S_{11}(1650)$	1650	125	0.008	0.77
$S_{11}(1895)$	1880	120	0.006	0.80
$S_{13}(1520)$	1520	110	0.003	0.75
$S_{13}(1700)$	1700	200	0.011	0.78
$S_{13}(1875)$	1875	200	1.554	0.70
$S_{13}(2120)$	2120	300	0.008	0.82

In-Medium Dynamics, Self-Energies, and Widths

- N, N* mean-field dynamics → static (time-like) vector fields (v) and scalar fields (s), i.e. $M_B \rightarrow M^*_B(\rho)$
- Mean-field couplings $f_{N^*Na} = f_{NNa}$ for a=s,v
- P-wave N* lead to purely transversal self-energies
- S-wave N* lead to longitudinal and transversal self-energies

$$\Sigma_L(w,\mathbf{q}) \equiv \Sigma_L^{(S)}(w,\mathbf{q})$$

$$\Sigma_T(w,\mathbf{q}) = \Sigma_T^{(S)}(w,\mathbf{q}) + \Sigma_T^{(P)}(w,\mathbf{q})$$

$$\Gamma_{L/T}(\mathbf{q}) = -\frac{1}{m_\omega} Im \left(\Sigma_{L/T}(E(\mathbf{q}),\mathbf{q})\right)$$

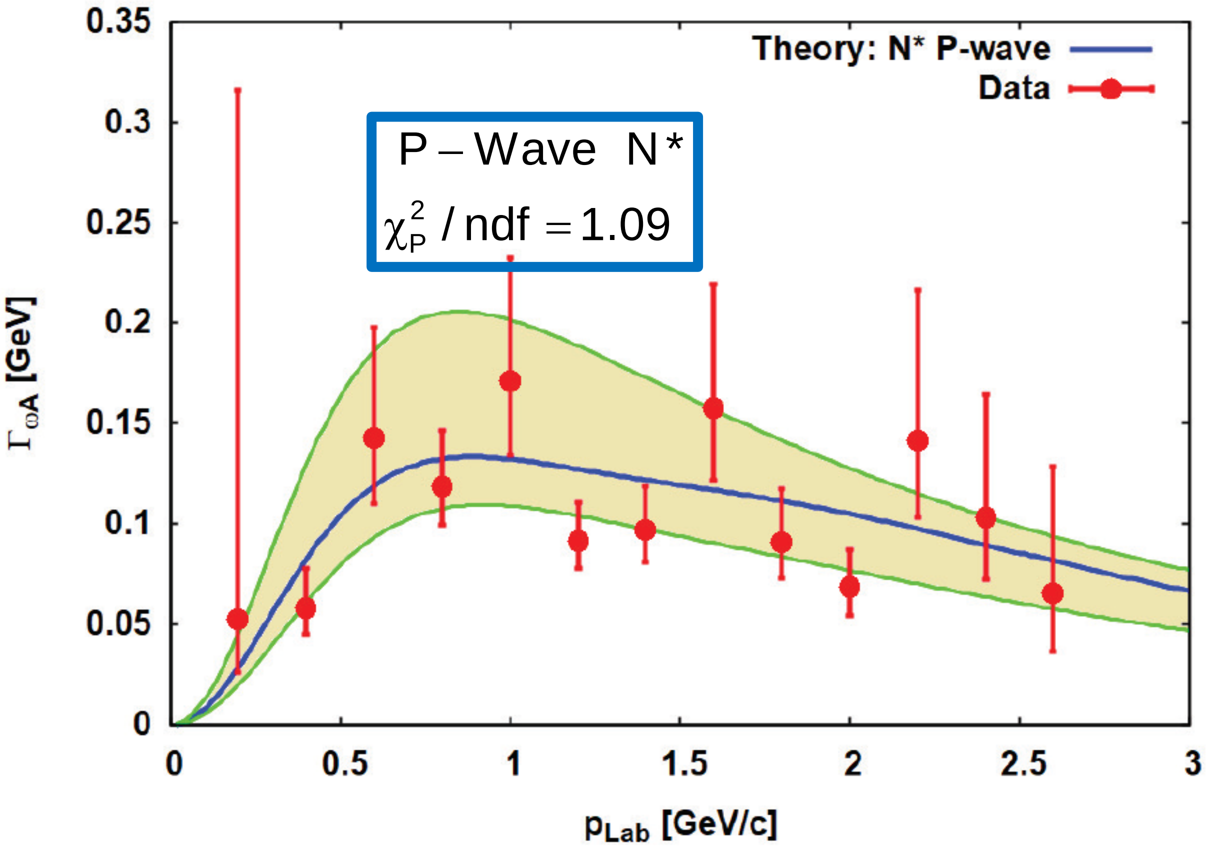
$$w = \sqrt{q^2 + m_\omega^2} \quad ; \quad q \rightarrow 0 :$$

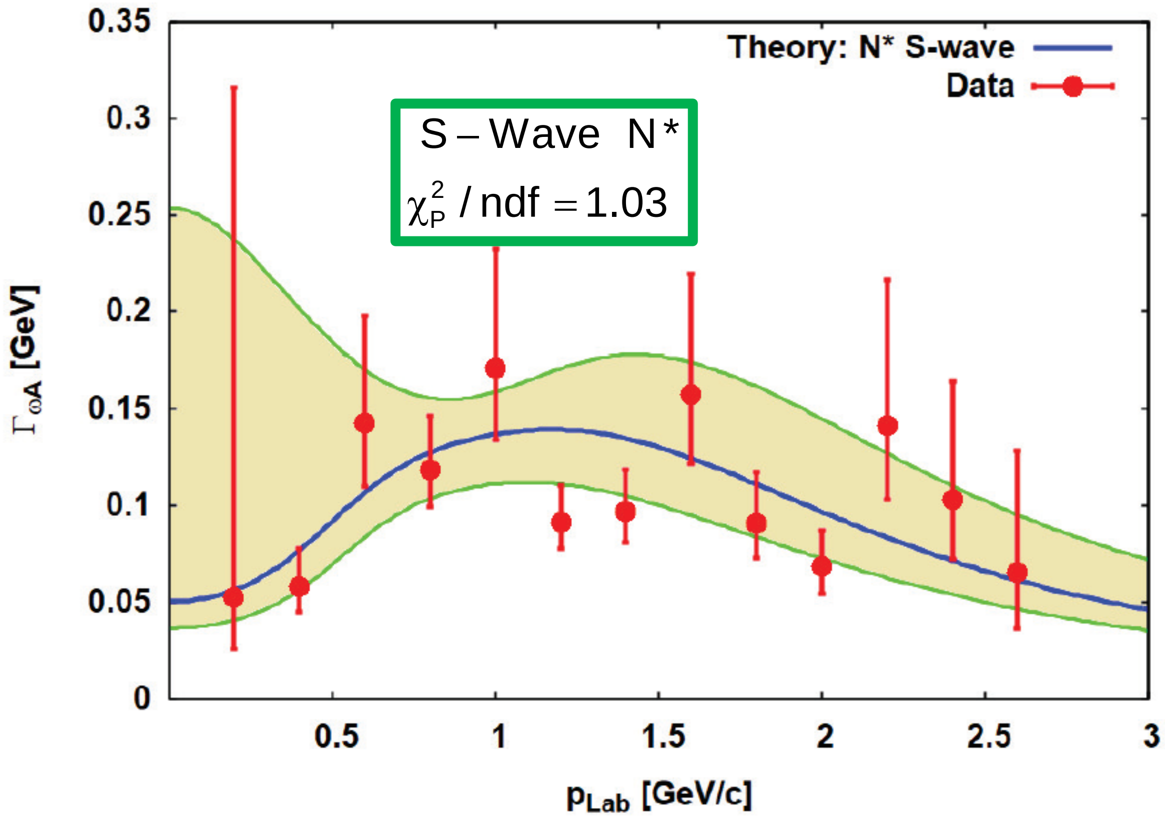
$$\Sigma_L^{(S)}(w,q) \approx \text{const.}$$

$$\Sigma_T^{(S)}(w,q) \approx \left(1 + \frac{q^2}{m_\omega^2}\right) \text{const.} \quad ; \quad \Sigma_T^{(P)}(w,q) \approx \frac{q^2}{m_\omega^2} \text{const}$$

Exploratory **Independent** P-wave and S-Wave Studies

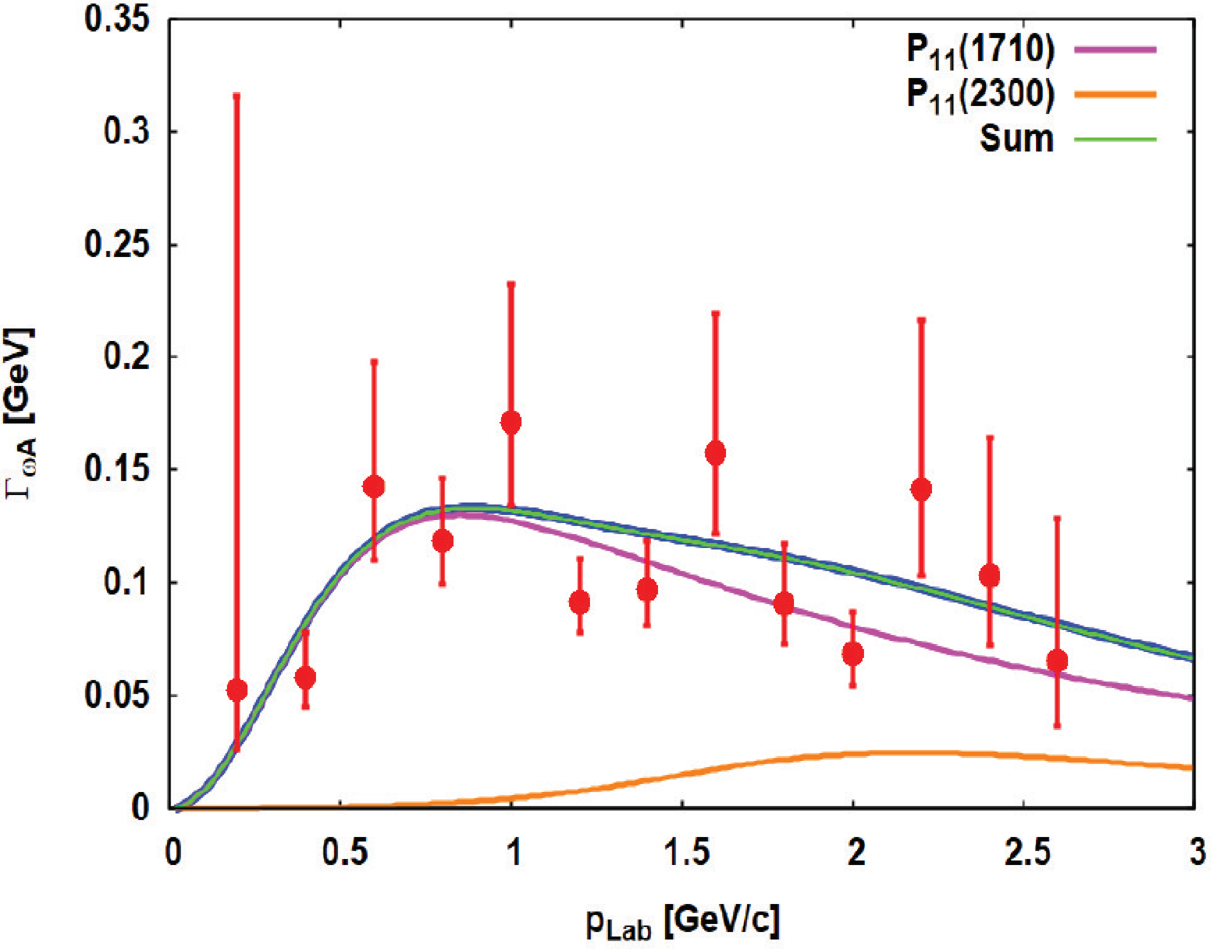
Independent P-wave and S-wave Fits to the observed Widths
(at central density of ^{93}Nb: ρ=0.140 fm^{-3})

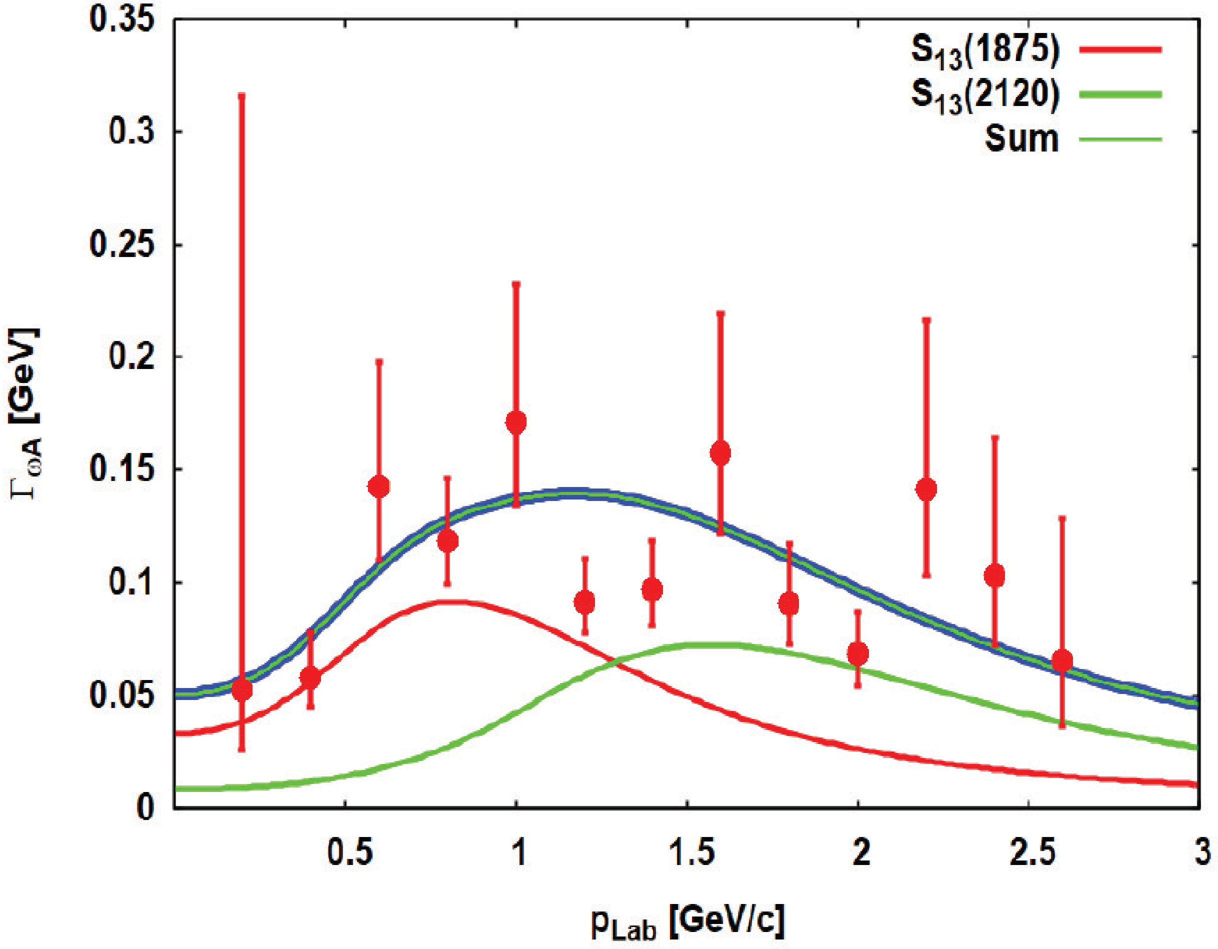




CBELSA/TAPS Data:
Friedrich et al., Eur. Phys. J. A (2016) 52: 297

Dominant P-wave and S-wave Components



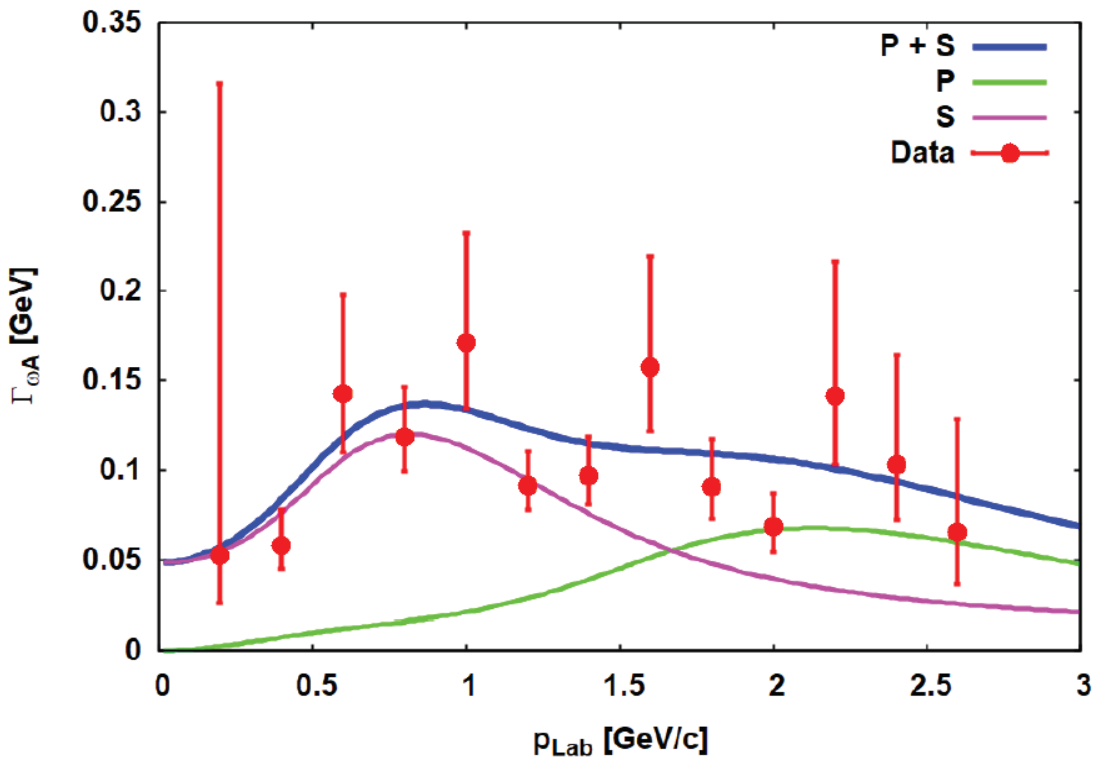


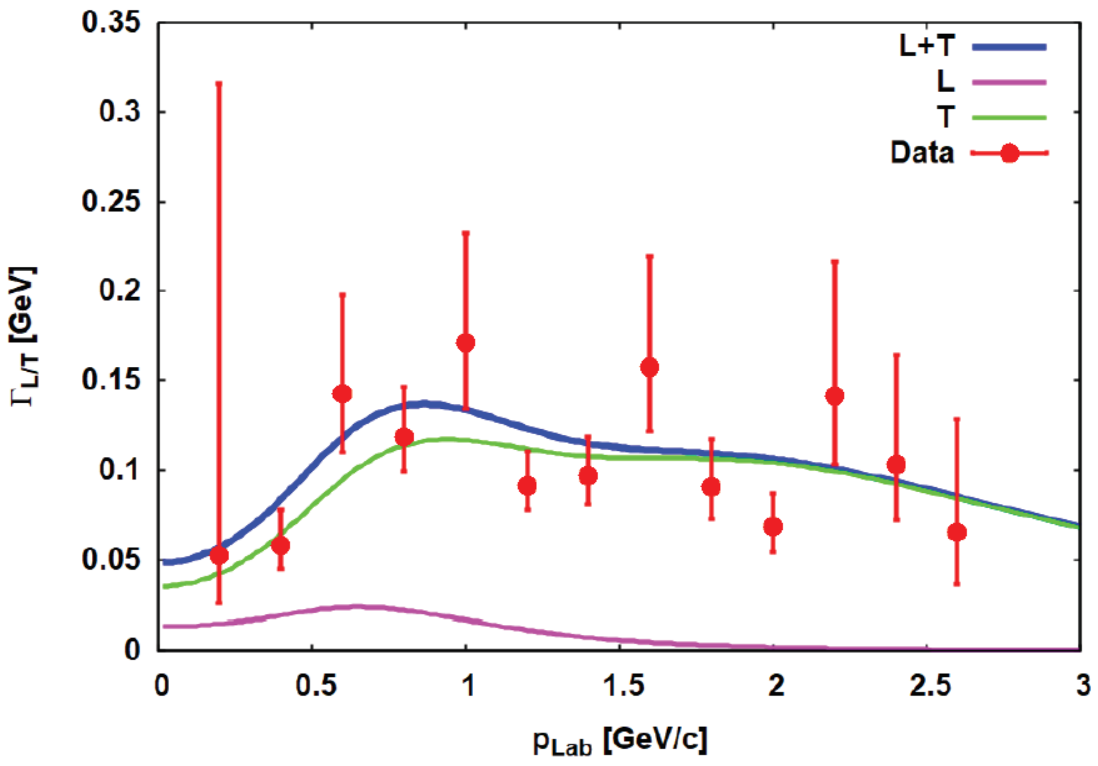
- **P-wave and S-wave polarization self-energies are compatible with the data**
- **The complete description must include both combined**
- **Width at threshold is decisive for and selective on the N* states**

Combined P-wave and S-wave Description

Results of Combined P- and S-wave Approach

Unconstrained Fit at ρ=0.140 fm^{-3} (χ^2=1.014)

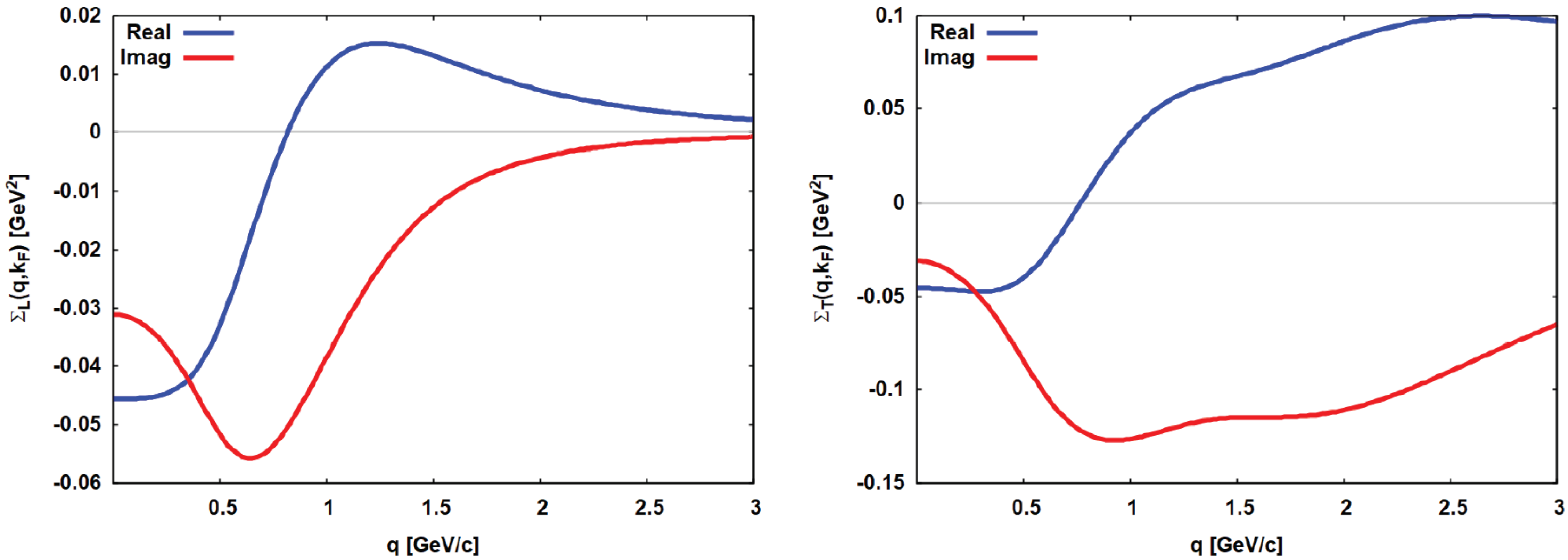




$$\Gamma_{thr} = \Gamma_{free} + \Gamma_A = 48.41\,\text{MeV}$$
$$\Rightarrow \Gamma_A = 39.73\ \text{MeV}$$

Self-Energies and Spectral Distributions

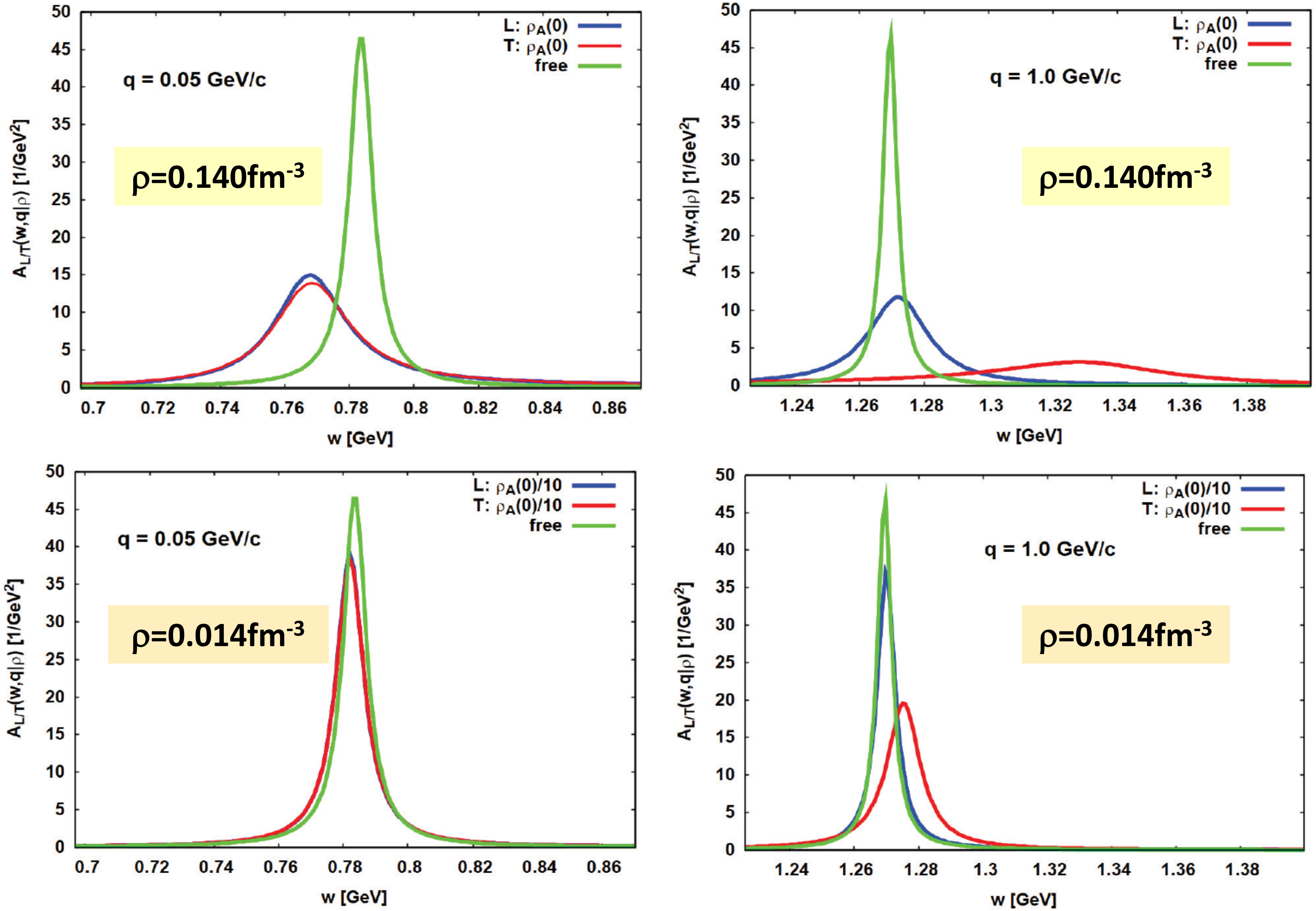
Energy Dependence of ω+A Polarization Self-Energies in the Center of ^{93}Nb
(ρ=0.14 fm^{-3})



- Re($\Sigma_{\omega A}$) change from attractive to repulsive
- Downward mass shifts close to threshold
- Upward mass shifts at higher energies

ω In-Medium Spectral Distributions

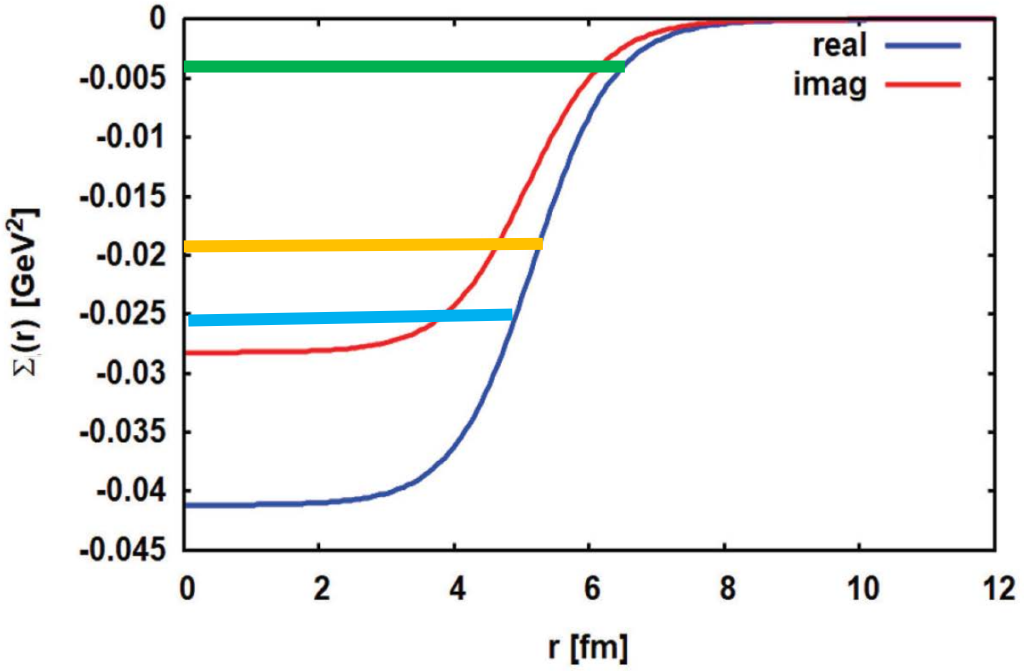
- At q = 0.05 GeV/c and central density (upper left) the distributions are moved to energies $\omega < m_w$
- At q = 1 GeV/c (upper right), A_L is centered close to A_{free}, A_T is shifted to $\omega > m_w$ with $\Gamma_T >> \Gamma_L$.
- At low densities (lower row), these differences prevail on a less pronounced level.



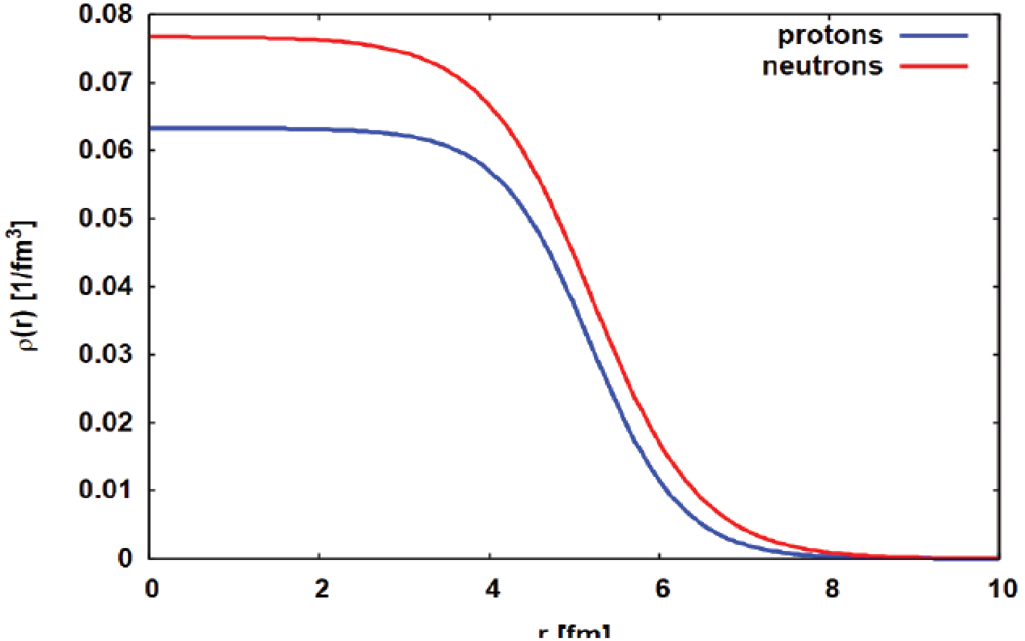
$$A_{L/T}(w,\mathbf{q}|\rho) = -\frac{1}{\pi}\,\mathrm{Im}\left(\frac{1}{w^2 - \mathbf{q}^2 - m_\omega^2 - \Sigma_{L/T}(w,\mathbf{q},k_F) - \Sigma_{free}(w,\mathbf{q})}\right)$$

$\omega + {}^{93}Nb$ Bound States?

ω+^{93}Nb Self-Energy at Threshold and Low-Energy Parameters



ω+^{93}Nb g.s. self-energies at threshold



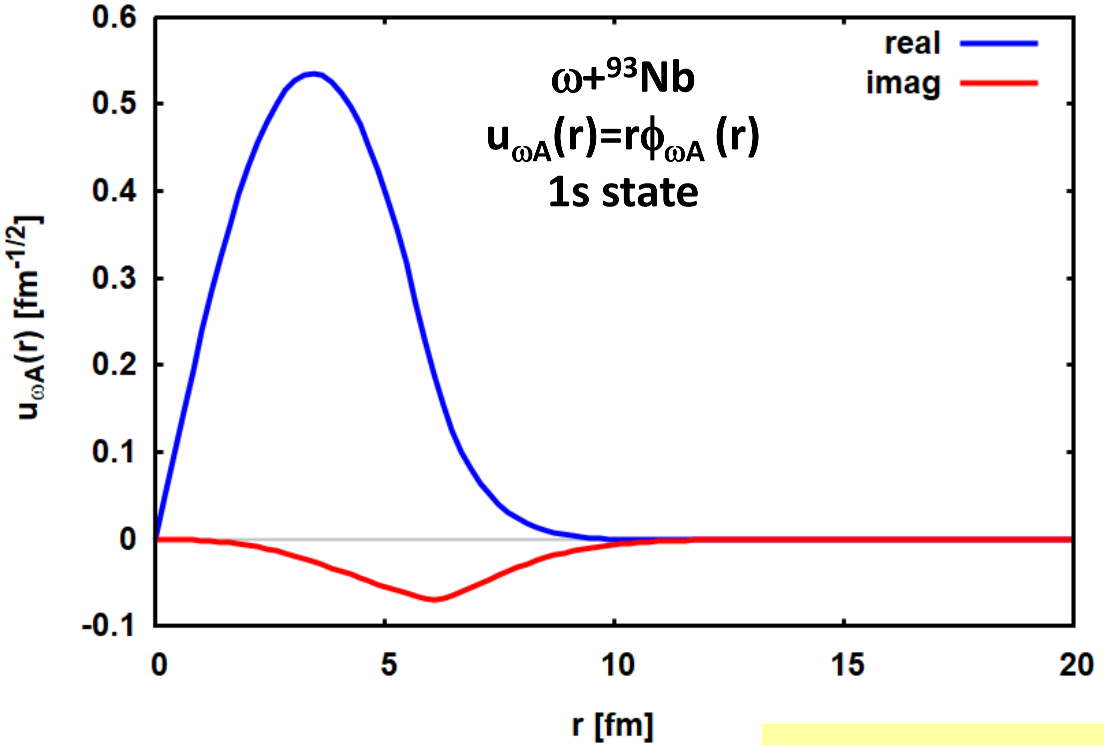
^{93}Nb RMF proton and neutron g.s densities

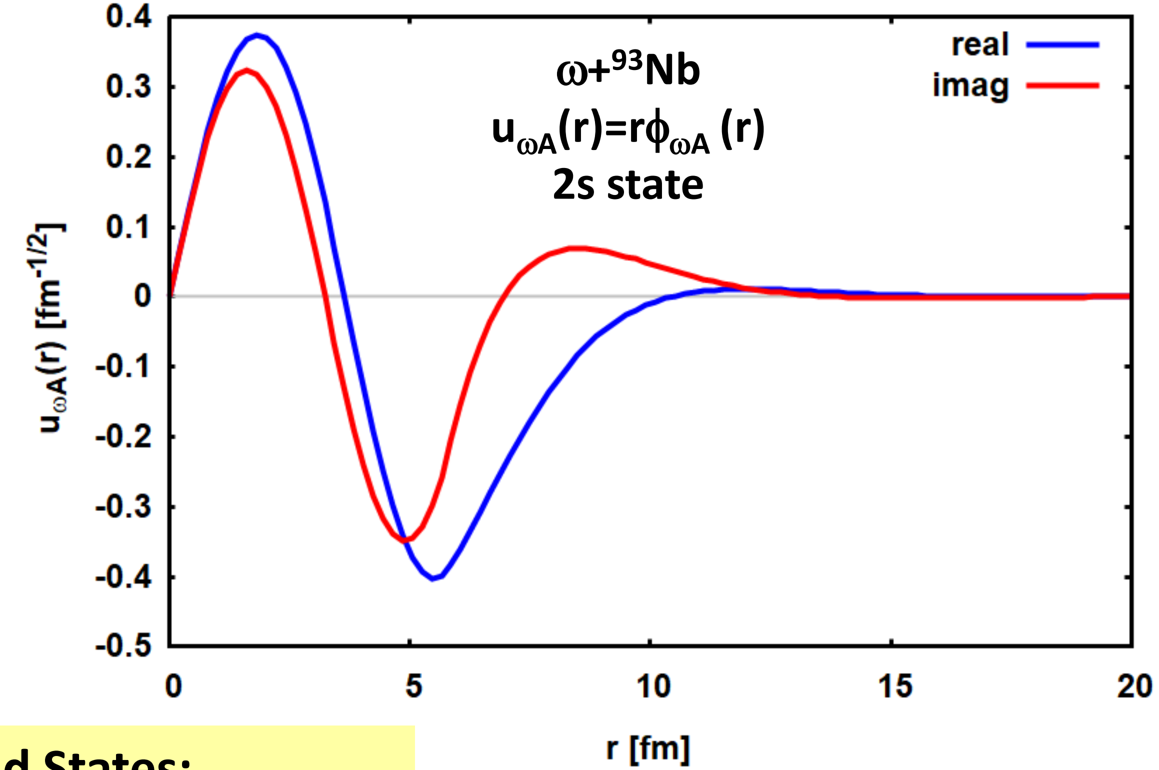
Low-energy Constants:

a_s = 5.6542 - i0.9041 fm and r_s = 3.7372 - i0.5183 fm

→ ε_B = -0.488 MeV ; Γ_B = 13.125 MeV

ω+^{93}Nb Bound States by Solution of the Wave Equation





Bound States:

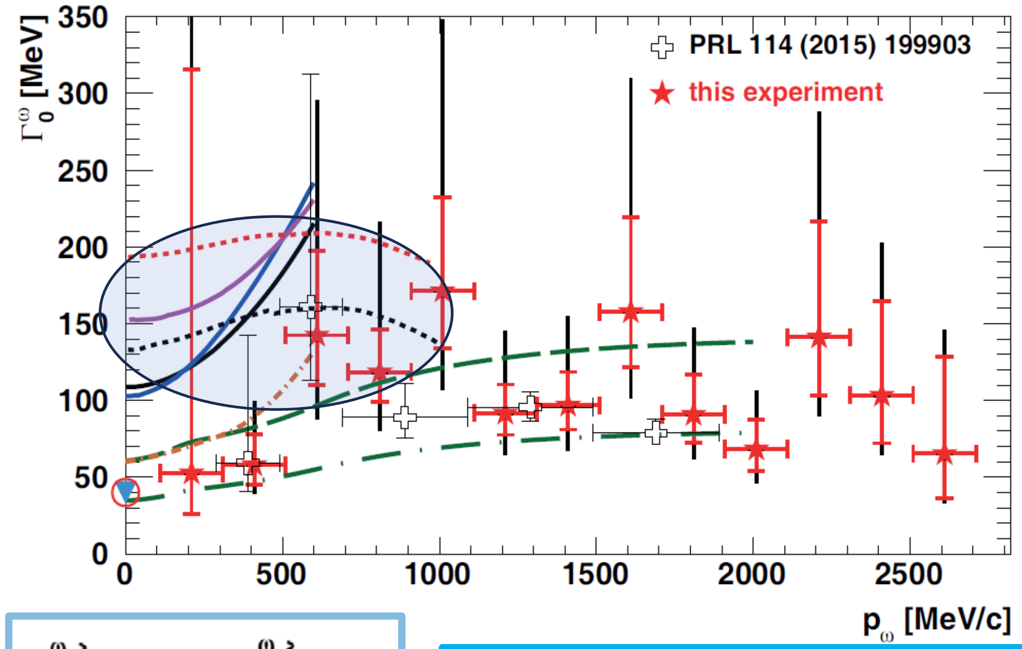
ε_B (2s)= - 1.910 - i12.027 MeV

ε_B (1p)= -11.804 - i13.575 MeV

ε_B (1s)= -17.266 - i14.136 MeV

$c\tau_{tot} \sim 5 \ldots 6$ fm << $c\tau_{free} \sim 22$ fm

Meson Cloud vs. Polarization Self-Energies



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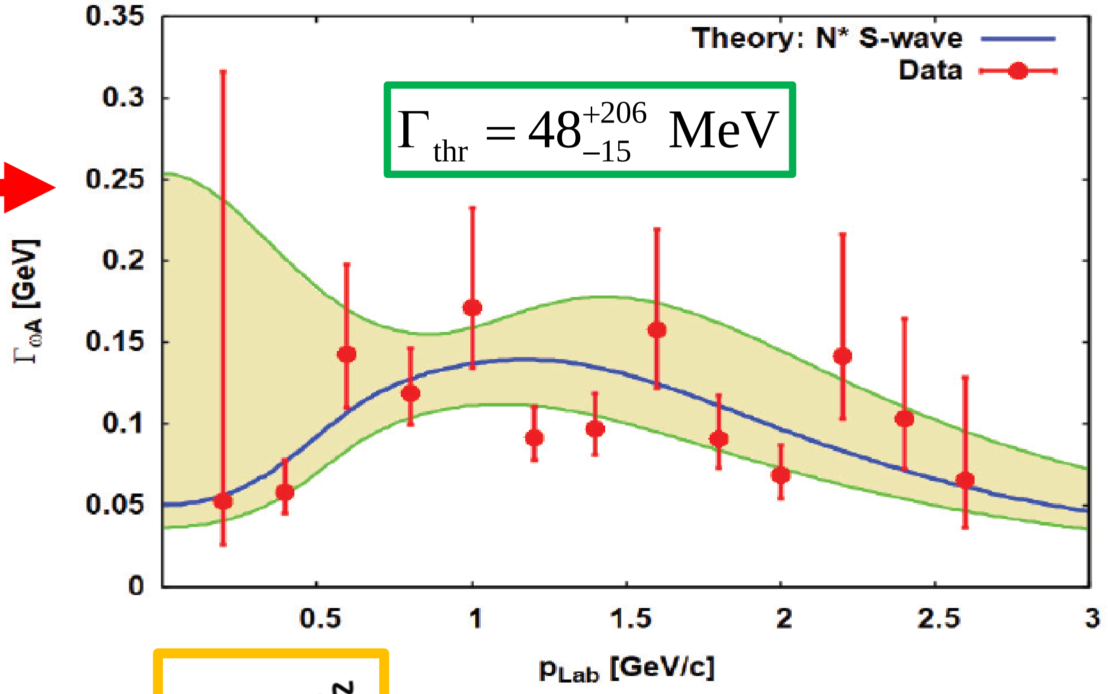
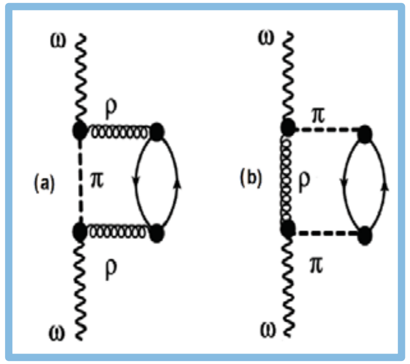
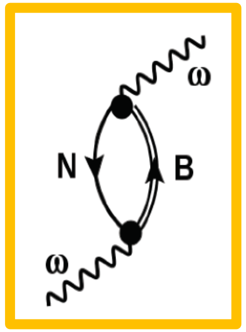




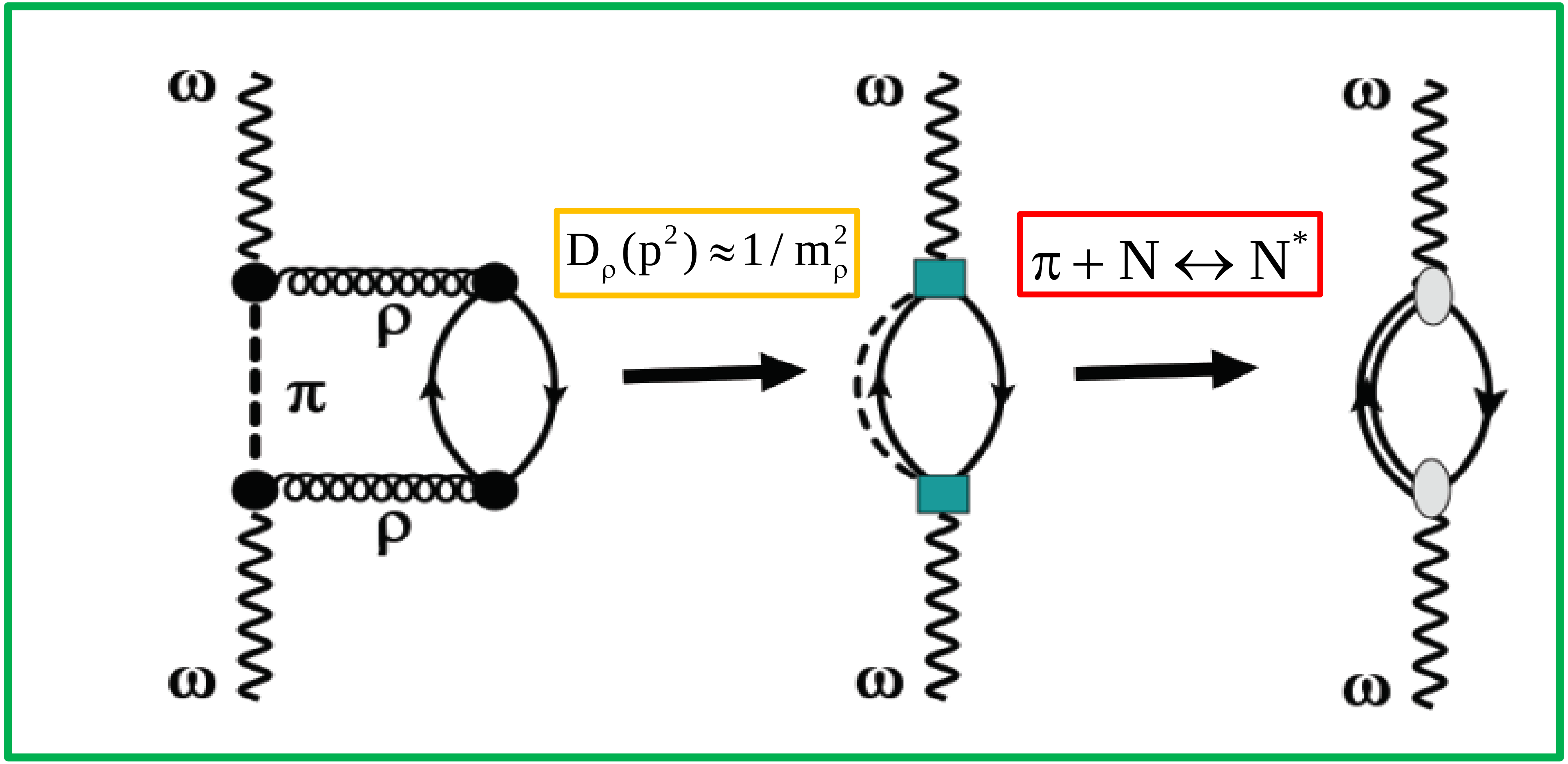
- Meson Cloud Self-energies
- Solid: Ramos et al., EPJ A 49, 148 (2013)
- Short dashed: Cabrera & Rapp, PLB 729, 67 (2014)



- Polarization Modes
- $\omega \rightarrow N^* N^{-1} \rightarrow \omega$
- see also left figure, Long dashed: Mühlich et al., NPA 780, 187 ('06)

from Friedrich et al., Eur. Phys. J. A (2016) 52: 297

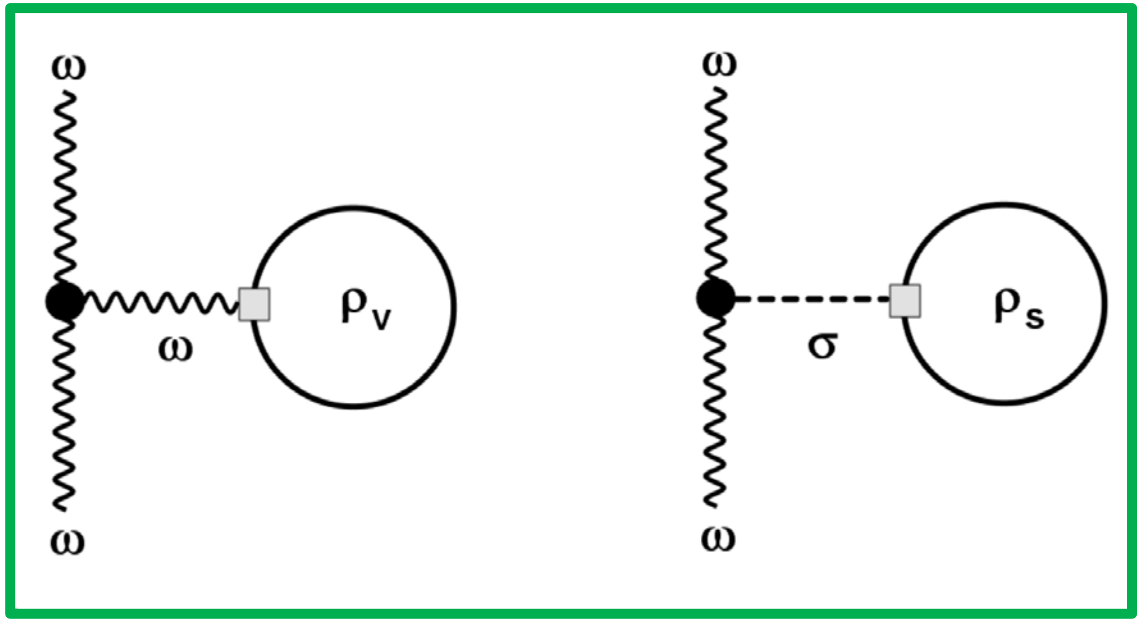
Overlap of N^*N^{-1} and Meson Cloud Self-Energies



Illustrating the relation of in-medium meson loops to baryon particle-hole loops for the $\omega \rightarrow \pi+\rho$ decay for the case where the rho-meson couples to an (isovector) excitation of the nuclear background medium.

…and what is missing?

…e.g. mean-field dynamics!



ωωω-Coupling unknown but from SU(3) symmetry

ωωσ-Coupling unknown but weak if σ ~ [ππ]

Summary

- ω-mesons in nuclear matter and a finite nucleus
- NN^{-1} and N^*N^{-1} polarization self-energies
- Spectral distributions in nuclear matter
- ω self-energies in ^{93}Nb
- ω- ^{93}Nb bound states
- Meson cloud and medium polarization

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Interactions of ω Mesons in Nuclear Matter and with Nuclei
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