The reaction $\pi N \to \omega N$ in a dynamical coupled-channel approach (17th International Workshop on Meson Physics)

June 26, 2023 | Yu-Fei Wang | Institute for Advanced Simulation, FZJ

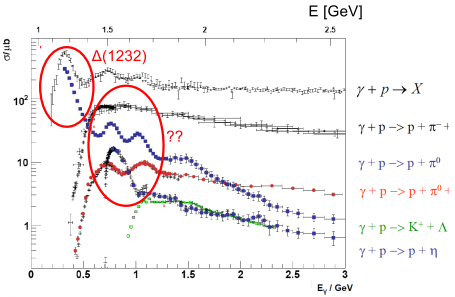
Outline

Based on Phys. Rev. D **106** 094031 (2022)
In collaboration with D. Rönchen, U.-G. Meißner, Y. Lu, C.-W. Shen, and J.-J. Wu

Introduction

Hadron spectroscopy

- Hadron spectroscopy → crucial for understanding QCD
- Low energy region → effective theories. High energy region → asymptotic freedom.
- Intermediate energy region → **abundant experimental observations**, **involved coupled-channel dynamics**
- Textbook Breit-Wigner (BW) description sometimes fails
  - resonance v.s. background
  - interference



[source: ELSA; data: ELSA, JLab, MAMI]

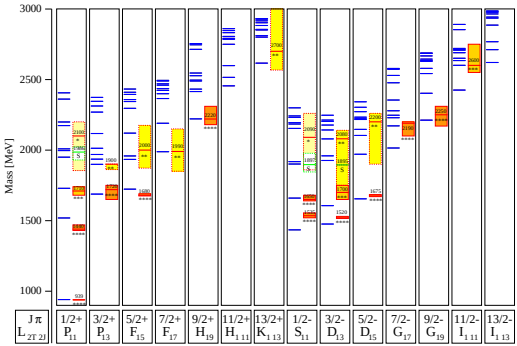
Introduction

Hadron spectroscopy

- Extraction of resonances $\rightarrow$ partial wave analyses (PWA)
- Decomposition under *JLS* basis

$$T \rightarrow T^{JLS}$$

- Various methods
  - Unitary isobar models $\rightarrow$ unitary amplitudes + BW
    [MAID, Yerevan/JLab, KSU, ...]
  - *K*-matrix Unitarization $\rightarrow$ on-shell intermediate states
    [GWU/SAID, BnGa, Gießen, ...]
  - Dynamical coupled-channel (DCC) approaches $\rightarrow$ interaction potentials + scattering equations (off-shell intermediate states)
    [ANL-Osaka (EBAC), Dubna-Mainz-Taipeh, ...] & Jülich-Bonn Model
  - . . .



[spectra: PDG 2000. quark model calculations: Löring *et. al.*, EPJA 10, 395 (2001)]

Introduction

Jülich-Bonn Model

Jülich-Bonn Model

- Powerful tool for the PWA
- Parameters $\longrightarrow$ fit to a worldwide collection of data
- Unitarity, analyticity $\longrightarrow$ searching resonance poles on the second sheet [Döring *et. al.*, NPA 829, 170 (2009)]
- Applications
  - Hadronic part: πN induced reactions [Schütz *et. al.*, PRC 51, 1374 (1995)] [Schütz *et. al.*, PRC 49, 2671 (1994)][Schütz *et. al.*, PRC 57, 1464 (1998)] [Krehl *et. al.*, PRC 62, 025207 (2000)] [Gasparyan *et. al.*, PRC 68, 045207 (2003)][Döring *et. al.*, NPA 851, 58 (2011)] [Rönchen *et. al.*, EPJA 49, 44 (2013)][Wang *et. al.*, PRD 106, 094031 (2022)]
  - Photoproduction [Rönchen *et. al.*, EPJA 50, 101 (2014)] [Rönchen *et. al.*, EPJA 51, 70 (2015)][Rönchen *et. al.*, EPJA 54, 110 (2018)] [Rönchen *et. al.*, EPJA 558, 229 (2022)]
  - Electroproduction (Jülich-Bonn-Washington) [Mai *et. al.*, PRC 103, 065204 (2021)] [Mai *et. al.*, PRC 106, 015201 (2022)]
  - Hidden charm sector and P_c states [Shen *et. al.*, CPC 42, 023106 (2018)] [Wang *et. al.*, EPJC 82, 497 (2022)]

ωN physics

- Low-density nuclear matter $\longrightarrow$ QCD chiral symmetry
- Vector meson dominance [Gell-Mann & Zachariasen, PR 124, 953 (1961)] $\longrightarrow$ ω in the nuclear matter
- ω plays a very important role in the EOS of the neutron stars [H. Shen *et. al.*, NPA 637, 435 (1998)]
- The ωN elastic scattering length $\longrightarrow$ in-medium bound states??

  Cannot be measured directly by experiments!! $\longrightarrow$ comprehensive models like Jülich-Bonn

Theoretical Framework

Dynamics I

Central part of this model: hadronic (πN induced) reactions

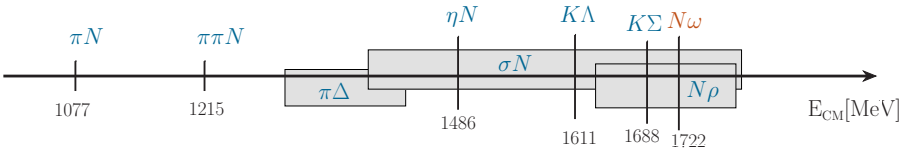
The Lippmann-Schwinger-like equation (CM frame)

$T_{\mu\nu}(p'', p', z) = V_{\mu\nu}(p'', p', z) + \sum_\kappa \int_0^\infty p^2 dp V_{\mu\kappa}(p'', p, z) G_\kappa(p, z) T_{\kappa\nu}(p, p', z)$

- Reaction channels $\nu \to \kappa \to \mu$ (after PW and isospin projection, *JLS* basis [Jacob & Wick, Annals Phys. 7, 404 (1959)],$J \leq 9/2$)
- Propagator: G ($\pi\pi N$ channel: effective channels $\rho N, \sigma N, \pi\Delta$. $E/\omega/z$ - baryon/meson/total energy.)

$$G_\kappa(z, p) = \begin{cases} (z - E_\kappa - \omega_\kappa + i0^+)^{-1} & \text{(if } \kappa \text{ is a two-body channel)}\,, \\ \left[z - E_\kappa - \omega_\kappa - \Sigma_\kappa(z, p) + i0^+\right]^{-1} & \text{(if } \kappa \text{ is an effective channel)}\,. \end{cases}$$

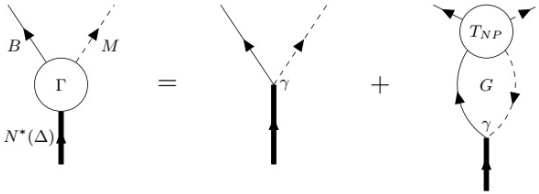
- Observables $\to$ dimensionless amplitude $\tau_{\mu\nu} = -\pi\sqrt{\rho_\mu \rho_\nu}\, T_{\mu\nu}$, ρ: kinematic factor
- Second Riemann sheet $\to$ analytical continuation of G [Döring *et. al.*, NPA 829, 170 (2009)]



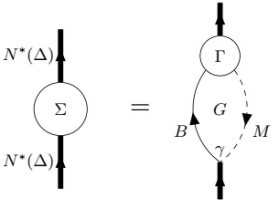
Theoretical Framework

Dynamics II

- Separating the amplitude
  $\rightarrow$ with/without s-channel poles $T = T^P + T^{NP}$
- $T^{NP} = V^{NP} + \sum \int p^2 dp V^{NP} G T^{NP}$
- $T^P_{\mu\nu}(p'', p', z) = \sum_{i,j} \Gamma^a_{\mu,i}(p'') D_{ij}(z) \Gamma^c_{\nu,j}(p')$,
  $(D^{-1})_{ij} = \delta_{ij}(z - m_i^b) - \Sigma_{ij}(z)$
  - $\Gamma(\gamma)$: the dressed (bare) vertices
    (a - annihilation, c - creation)
  - Σ: self-energy functions
  - Nucleon mass renormalization
- $V^{NP}, \gamma \rightarrow$ constructed from effective Lagrangians
  $+$ regulators (cut-offs)
  (details: Supplemental material
  [Wang *et. al.*, PRD 106, 094031 (2022)])
- s-channel contact terms: $D \sim (1 - \Sigma)^{-1}$
  [Rönchen *et. al.*, EPJA 51, 70 (2015)]



(a) The vertex.



(b) The self energy.

Numerical results

Numerical details

- Database $\rightarrow$ over 9000 points, 174 of $\pi N \rightarrow \omega N$
  Energy $\in [1078, 2300]$ MeV
- Parameters: s-channel bare couplings + cut-offs (V^{NP})
  $\rightarrow 225 + 79$
- Haftl-Tabakin matrix inversion
  $\rightarrow$ discretization via the Gaussian points

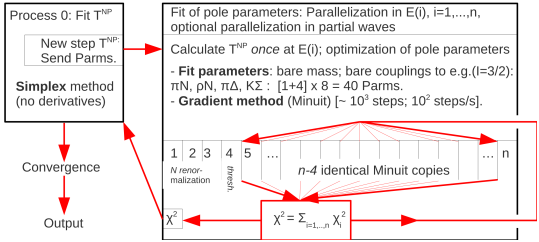
  [Haftel & Tabakin, NPA 158, 1 (1970)]

$$T^{NP}_{ab} = V^{NP}_{ab} + \sum_{i=1}^{n} p_i^2 w_i V^{NP}_{ai} G_i T^{NP}_{ib}\,, \quad \hat{T} = (1 - \hat{V}\hat{G})^{-1}\hat{V}$$

- Supercomputer JURECA

  [JSC, Journal of large-scale research facilities 7 (2021)]

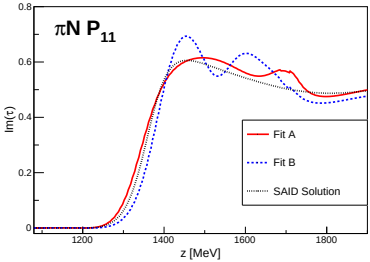
- *NP* parameters are much slower $\rightarrow$ nested fitting

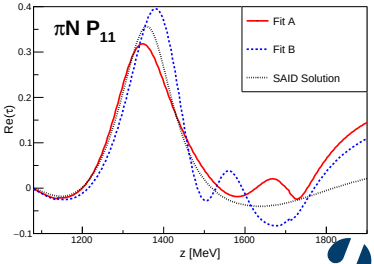


Numerical fit

Estimation of the errors

- The statistics
  - Energy-dependent solutions of πN amplitudes [Arndt *et. al.*, PRC 74, 045205 (2006)] $\longrightarrow$ no errors
  - Some problematic data points of ηN [Brown *et. al.*, NPB 153, 89 (1979)]
  - Extra weights on important data sets (e.g. ωN)
  - Impossible to switch on all parameters in one attempt
  - Estimation of the uncertainties $\longrightarrow$ fits with different initial values
- Two fits $\longrightarrow$ equally good fit qualities
  - Fit A $\longrightarrow$ from intermediate values of [Röchen *et. al.*, EPJA 54, 110 (2018)]
  - Fit B $\longrightarrow$ an extra narrow resonance in P_{11} wave ($J^P = \frac{1}{2}^+$, $z_r = 1585 - 35i$ MeV)





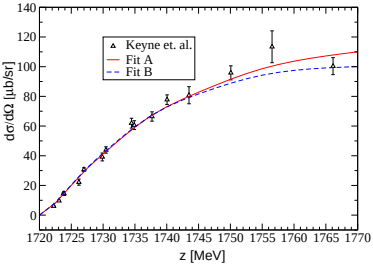
Numerical fit

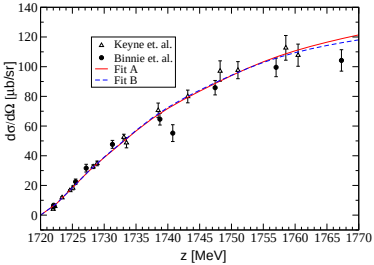
Fit Results

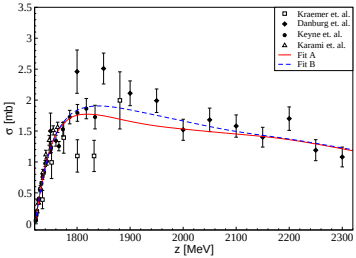
ωN Data: [Danburg *et. al.*, PRD 2, 2564 (1970)] [Kraemer *et. al.*, PR 136, B496 (1964)] [Binnie *et. al.*, PRD 8, 2789 (1973)] [Keyne *et. al.*, PRD 14, 28 (1976)] [Karami *et. al.*, NPB 154, 503 (1979)]

Other channels: see the website

First: backward differential cross section. Second: forward. Third: total cross section.







Numerical fit

Fit Results

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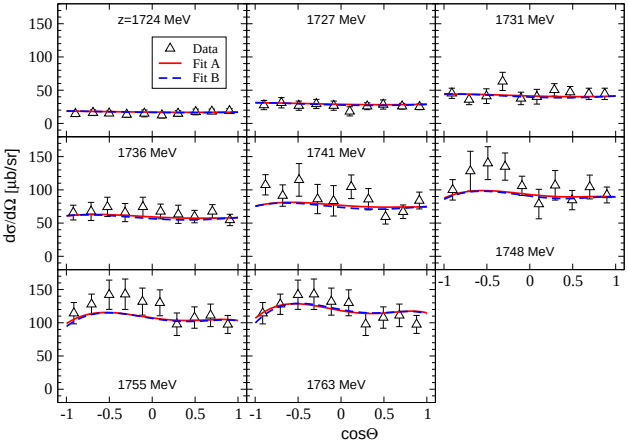
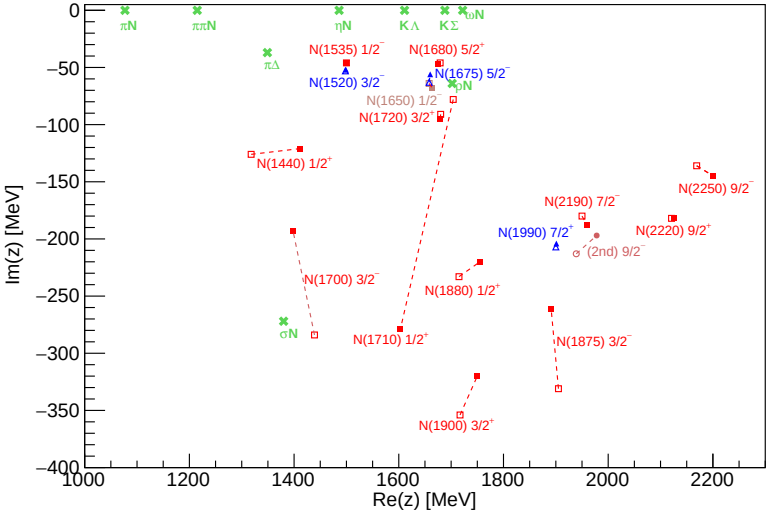
Other channels: see the website



Selected Results

N^* Spectra (J^P convention. Empty symbols: fit A. Filled: fit B.)



Selected Results

N^* Couplings

Physical couplings $\rightarrow$ normalized residues at $z_r = M_r - \frac{i}{2}\Gamma_r$ [PDG] $\tau^{II}_{\mu\nu} \sim \frac{R_\mu R_\nu}{z_r - z} + \cdots$, $NR_\mu \equiv \frac{2R_{\pi N}}{\Gamma_r} \times R_\mu$

Our results

- ωN mainly couples to lower states ($|NR| > 0.5$): $N(1535)\ \frac{1}{2}^-$, $N(1710)\ \frac{1}{2}^+$ and $N(1680)\ \frac{5}{2}^+$
- Very large bare couplings $\rightarrow$ $N^*(1535)$ and $N^*(1710)$
- Fit C (constraining the bare couplings) failed $\rightarrow$ left for the future with photonproduction included
- Higher states $\rightarrow$ $N(2250)\ \frac{9}{2}^-$ relatively important ($Br > 10\%$)

In the literature: which states are important for ωN

- $N(1720)\ \frac{3}{2}^+$ and $N(1680)\ \frac{5}{2}^+$ [Zhao, PRC 63, 025203 (2001)]
- $N(1535)\ \frac{1}{2}^-$, $N(1650)\ \frac{1}{2}^-$ and $N(1520)\ \frac{3}{2}^-$ [Lutz *et. al.*, NPA 706, 431 (2002)]
- $N(1710)\ \frac{1}{2}^+$, $N(1675)\ \frac{5}{2}^-$ and $N(1680)\ \frac{5}{2}^+$ [Penner & Mosel, PRC 66, 055211 (2002)][Penner & Mosel, PRC 66, 055212 (2002)] [Shklyar *et. al.*, PRC 71, 055206 (2005)]
- $N(1675)\ \frac{5}{2}^-$ and $N(1680)\ \frac{5}{2}^+$ $\rightarrow$ very large bare couplings [Muehlich *et. al.*, NPA 780, 187 (2006)]

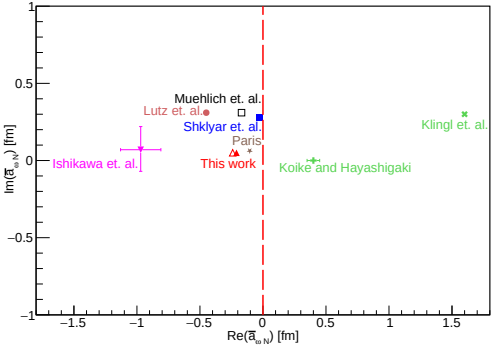
Selected Results

ωN Scattering Length

- Definition $\rightarrow a_\kappa \equiv \lim_{p_\kappa \rightarrow 0} p_\kappa^{-1} \tan \tilde{\delta}_\kappa^{(L=0)} = \lim_{p_\kappa \rightarrow 0} p_\kappa^{-1} \tau_{\kappa\kappa}^{(L=0)}$ ($\tilde{\delta}$: generalized phase shift)
- Spin average of $\omega N \rightarrow \bar{a}_{\omega N} = \frac{1}{3} a_{\omega N}\left(S = \frac{1}{2}\right) + \frac{2}{3} a_{\omega N}\left(S = \frac{3}{2}\right)$
- Fit A: $\bar{a}_{\omega N} = (-0.24 + 0.05i)$ fm. Fit B: $\bar{a}_{\omega N} = (-0.21 + 0.05i)$ fm.
- Re$\bar{a} < 0 \rightarrow$ in-medium bound states tend not to be formed

Other results: [Koike & Hayashigaki, PTP 98, 631 (1997)][Klingl *et. al.*, NPA 650, 299 (1999)] [Lutz *et. al.*, NPA 706, 431 (2002)][Shklyar *et. al.*, PRC 71, 055206 (2005)]

[Muehlich *et. al.*, NPA 780, 187 (2006)][Paris, PRC 79, 025208 (2009)] [Ishikawa *et. al.*, PRC 101, 052201 (2020)]



Conclusion and Outlook

Conclusion

- The Jülich-Bonn Model: a powerful model for the partial-wave analyses and extraction of the hadron spectra
- Study of the ωN channel
  - More than 9000 data points in πN induced reactions are refitted.
  - There are two fit solutions to evaluate the uncertainties.
  - Hadron spectra are reanalysed.
  - ωN couples mainly to lower states: $N(1535)\ \frac{1}{2}^-$, $N(1710)\ \frac{1}{2}^+$ and $N(1680)\ \frac{5}{2}^+$.
  - Negative real part of the scattering length of ωN.

Outlook

- ω photonproduction $\rightarrow$ abundant and precise experimental measurements
- Numerical fit of the hidden charm sector
- Study of $\bar{K}N$ induced reactions
- More statistics $\rightarrow$ πN correlation matrix [Döring *et. al.*, PRC 93, 065205 (2016)]
- LASSO method [Tibshirani, Statistics in medicine 16, 385 (1997)]
- The ω meson in the nuclear matter


Thank
you

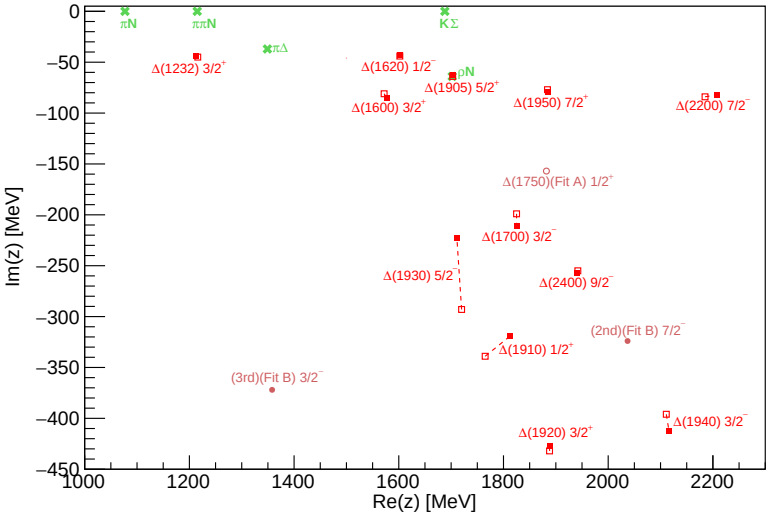
Backups

Feynman diagrams

	πN	$\pi\Delta$	σN	ηN	$K\Lambda$	$K\Sigma$	ρN	ωN
πN	$\rho\sigma$	ρ	π	a_0	K^*	K^*	$\pi\omega a_1$	ρ
$\pi\Delta$	—	ρ	π				π	
σN	—	—	σ					
ηN	—	—	—	f_0	K^*	K^*		ω
$K\Lambda$	—	—	—	—	$f_0\omega$	ρa_0		KK^*
$K\Sigma$	—	—	—	—	—	$f_0\omega\rho a_0$		KK^*
ρN	—	—	—	—	—	—	ρ	
ωN	—	—	—	—	—	—	—	σ

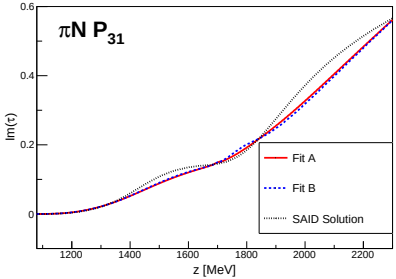
	πN	$\pi\Delta$	σN	ηN	$K\Lambda$	$K\Sigma$	ρN	ωN
πN	$N\Delta$	$N\Delta$	N	N	$\Sigma\Sigma^*$	$\Lambda\Sigma\Sigma^*$	$N\Delta$	N
$\pi\Delta$	—	$N\Delta$					N	
σN	—	—	N					
ηN	—	—	—	N	Λ	$\Sigma\Sigma^*$		N
$K\Lambda$	—	—	—	—	$\Xi\Xi^*$	$\Xi\Xi^*$		Λ
$K\Sigma$	—	—	—	—	—	$\Xi\Xi^*$		$\Sigma\Sigma^*$
ρN	—	—	—	—	—	—	$N\Delta$	
ωN	—	—	—	—	—	—	—	N

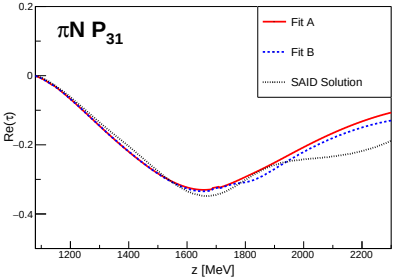
Δ spectra


πN
ππN
πΔ
KΣ
ρN
Δ(1232) 3/2+
Δ(1620) 1/2−
Δ(1905) 5/2+
Δ(1600) 3/2+
Δ(1950) 7/2+
Δ(2200) 7/2−
Δ(1750)(Fit A) 1/2+
Δ(1700) 3/2−
Δ(1930) 5/2
Δ(2400) 9/2−
(2nd)(Fit B) 7/2−
Δ(1910) 1/2+
(3rd)(Fit B) 3/2−
Δ(1940) 3/2−
Δ(1920) 3/2+
Im(z) [MeV]
Re(z) [MeV]
0
−50
−100
−150
−200
−250
−300
−350
−400
−450
1000
1200
1400
1600
1800
2000
2200

Δ spectra

- Influence of $\omega N \to$ rearrangement of $I = 1/2, 3/2$ contributions via $K^0\Sigma^0$ and $K^+\Sigma^-$
- Channels of isospin $I = 3/2 \to$ smaller database
- The $\Delta(1910)\,\frac{1}{2}^+$ (P_{31} wave of πN) $\to$ much broader $1765 - 339i(1813 - 319i)$ MeV while the line-shape is well described





Pole positions

Resonances	Fit A	Fit B	Estimation of PDG
$N(1535)\ \frac{1}{2}^-$	$1500 - 46i$	$1499 - 46i$	$1510 - 65i$ (****)
$N(1650)\ \frac{1}{2}^-$	$1658 - 64i$	$1664 - 68i$	$1655 - 68i$ (****)
$N(1440)\ \frac{1}{2}^+$ (NP)	$1318 - 126i$	$1411 - 121i$	$1370 - 88i$ (****)
$N(1710)\ \frac{1}{2}^+$	$1704 - 78i$	$1603 - 279i$	$1700 - 60i$ (****)
$N(1880)\ \frac{1}{2}^+$ (NP)	$1715 - 233i$	$1755 - 220i$	$1860 - 115i$ (***)
$N(1720)\ \frac{3}{2}^+$	$1680 - 91i$	$1679 - 95i$	$1675 - 125i$ (****)
$N(1900)\ \frac{3}{2}^+$	$1717 - 354i$	$1750 - 320i$	$1920 - 75i$ (****)
$N(1520)\ \frac{3}{2}^-$	$1498 - 53i$	$1499 - 52i$	$1510 - 55i$ (****)
$N(1700)\ \frac{3}{2}^-$ (NP)	$1439 - 284i$	$1398 - 193i$	$1700 - 100i$ (***)
$N(1875)\ \frac{3}{2}^-$ (NP)	$1905 - 331i$	$1891 - 261i$	$1900 - 80i$ (***)
$N(1675)\ \frac{5}{2}^-$	$1658 - 63i$	$1660 - 56i$	$1660 - 68i$ (****)
$N(1680)\ \frac{5}{2}^+$	$1679 - 46i$	$1674 - 47i$	$1675 - 60i$ (****)
$N(1990)\ \frac{7}{2}^+$	$1900 - 207i$	$1901 - 204i$	omitted (**)
$N(2190)\ \frac{7}{2}^-$	$1950 - 180i$	$1960 - 188i$	$2100 - 200i$ (****)
$N(2250)\ \frac{9}{2}^-$	$2169 - 136i$	$2201 - 145i$	$2200 - 210i$ (****)
2nd pole $\frac{9}{2}^-$ (NP)	$1939 - 213i$	$1978 - 197i$	—
$N(2220)\ \frac{9}{2}^+$	$2121 - 182i$	$2125 - 182i$	$2170 - 200i$ (****)

Pole positions

Resonances	Fit A	Fit B	Estimation of PDG
$\Delta(1620)\ \frac{1}{2}^-$	$1602 - 44i$	$1602 - 43i$	$1600 - 60i$ (****)
$\Delta(1750)\ \frac{1}{2}^+$ (NP)	$1882 - 157i$	—	omitted (*)
$\Delta(1910)\ \frac{1}{2}^+$	$1765 - 339i$	$1813 - 319i$	$1860 - 150i$ (****)
$\Delta(1232)\ \frac{3}{2}^+$	$1216 - 45i$	$1213 - 44i$	$1210 - 50i$ (****)
$\Delta(1600)\ \frac{3}{2}^+$ (NP)	$1572 - 81i$	$1577 - 85i$	$1510 - 135i$ (****)
$\Delta(1920)\ \frac{3}{2}^+$	$1888 - 432i$	$1888 - 427i$	$1900 - 150i$ (***)
$\Delta(1700)\ \frac{3}{2}^-$	$1825 - 199i$	$1825 - 211i$	$1665 - 125i$ (****)
$\Delta(1940)\ \frac{3}{2}^-$ (NP)	$2111 - 396i$	$2116 - 412i$	$1950 - 175i$ (**)
3rd pole $\frac{3}{2}^-$ (NP)	—	$1358 - 372i$	—
$\Delta(1930)\ \frac{5}{2}^-$	$1720 - 293i$	$1711 - 223i$	$1880 - 140i$ (***)
$\Delta(1905)\ \frac{5}{2}^+$	$1703 - 64i$	$1703 - 63i$	$1800 - 150i$ (****)
$\Delta(1950)\ \frac{7}{2}^+$	$1884 - 77i$	$1885 - 79i$	$1880 - 120i$ (****)
$\Delta(2200)\ \frac{7}{2}^-$	$2185 - 84i$	$2208 - 82i$	$2100 - 170i$ (***)
2nd pole $\frac{7}{2}^-$ (NP)	—	$2037 - 324i$	—
$\Delta(2400)\ \frac{9}{2}^-$	$1942 - 255i$	$1941 - 257i$	omitted (**)

Normalized residues: ωN channel

TABLE V. The normalized residues of the N^* states for the ωN channel. The values are written in the form (NR, θ), with the phase θ in units of degrees. In each cell, the first (second) value is from fit A (B). The three sub-channels are (1)$|J-L| = \frac{1}{2}, S = \frac{1}{2}$; (2)$|J-L| = \frac{1}{2}, S = \frac{3}{2}$; (3)$|J-L| = \frac{3}{2}, S = \frac{3}{2}$.

Resonances	Channel (1)	Channel (2)	Channel (3)
$N(1535)\frac{1}{2}^-$	(1.13, −156°) (1.13, −163°)	0	(0.14, 26°) (0.13, 18°)
$N(1650)\frac{1}{2}^-$	(0.19, 156°) (0.14, 148°)	0	(0.02, −9°) (0.02, −10°)
$N(1440)\frac{1}{2}^+$	(0.18, −37°) (0.21, 23°)	(0.34, 1°) (0.42, 64°)	0
$N(1710)\frac{1}{2}^+$	(0.10, 158°) (0.27, −86°)	(0.56, −172°) (0.73, −59°)	0
$N(1880)\frac{1}{2}^+$	(0.01, −24°) (0.00, 152°)	(0.03, 31°) (0.02, 157°)	0
$N(1720)\frac{3}{2}^+$	(0.01, 150°) (0.01, 155°)	(0.05, −178°) (0.06, −178°)	(0.00, 69°) (0.00, 56°)
$N(1900)\frac{3}{2}^+$	(0.00, 33°) (0.01, −19°)	(0.02, 138°) (0.01, 91°)	(0.00, 6°) (0.00, −75°)
$N(1520)\frac{3}{2}^-$	(0.09, 139°) (0.14, 141°)	(0.04, 102°) (0.07, 115°)	(0.16, −108°) (0.22, −99°)
$N(1700)\frac{3}{2}^-$	(0.02, −35°) (0.03, 20°)	(0.01, −123°) (0.01, 5°)	(0.02, −4°) (0.01, 87°)
$N(1875)\frac{3}{2}^-$	(0.00, −110°) (0.00, −82°)	(0.00, −172°) (0.00, −114°)	(0.00, −157°) (0.00, −105°)
$N(1675)\frac{5}{2}^-$	(0.01, 108°) (0.01, 117°)	(0.25, 82°) (0.30, 89°)	(0.00, −51°) (0.00, −48°)
$N(1680)\frac{5}{2}^+$	(0.00, −8°) (0.00, −32°)	(0.04, 31°) (0.04, 26°)	(0.95, 165°) (0.98, 162°)
$N(1990)\frac{7}{2}^+$	(0.00, −46°) (0.00, −42°)	(0.04, −60°) (0.04, −62°)	(0.00, −105°) (0.00, −107°)
$N(2190)\frac{7}{2}^-$	(0.00, −155°) (0.00, −149°)	(0.01, 146°) (0.01, 154°)	(0.07, 177°) (0.03, 177°)
$N(2250)\frac{9}{2}^-$	(0.01, −31°) (0.01, −47°)	(0.12, −28°) (0.16, −38°)	(0.00, −42°) (0.01, −52°)
2nd pole $\frac{9}{2}^-$	(0.00, 92°) (0.00, 83°)	(0.06, 85°) (0.05, 78°)	(0.00, 44°) (0.00, 44°)
$N(2220)\frac{9}{2}^+$	(0.00, 50°) (0.00, 58°)	(0.01, 10°) (0.01, 14°)	(0.03, 21°) (0.03, 24°)