

# 低能强子散射研究的新进展

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- 1  $\pi$  N scatterings
- 2 The sub-threshold resonance:  $N^*(920)$ 
  - PKU representation
  - Roy-Steiner equation analysis
- 3  $\pi\pi$  phase shift at un-physical pion masses
- 4 Temperature and Density

# $\pi N$ SCATTERINGS

- Problems to study

- Low energy properties:

$\pi N$   $\sigma$ -term, subthreshold expansions

[C. Ditsche et. al. 2012 JHEP][Y. H. Chen et. al. 2013 PRD][Hoferichter et. al. 2016 Phys. Rept.]

- Intermediate resonances:  $\Delta(1232)$ ,  $N^*(1440)$ ,  $N^*(1535) \dots$

- Methods

- Perturbative calculation

$O(p^3)$  [J.M. Alarcón et. al. 2012 RPD];  $O(p^4)$  [Y. H. Chen et. al. 2013 PRD]

- Couple channel Lippmann-Schwinger Equation

- Dispersion technique

- Roy-Steiner equation

[C. Ditsche et. al. 2012 JHEP][Hoferichter et. al. 2016 Phys.Rept.]

# $\pi N$ SCATTERINGS

$S_{11}$  and  $P_{11}$  channels:

- $S_{11}$  channel ( $L_{2I} 2J$  convention):  $N^*(1535)$   
[N. Kaiser et. al. 1995 PLB][J. Nieves et. al. 2000 PRD]
  - lies above the  $P$ - wave first resonance  $N^*(1440)$
  - large couple channel effects with  $\pi N$  and  $\eta N$
- $P_{11}$  channel:  $N^*(1440)$  (Ropper resonance), various puzzles
  - low mass, large decay width, coupling to  $\sigma N$  channel... [O. Krehl et. al. 2000 PRC]
  - two-pole structure? [R. A. Arndt et. al. 1985 PRD]
  - second sheet complex branch cut in  $P_{11}$  channel?  
[S. Ceci et. al. 2011 PRC]
- A method is needed to examine the relevant channels carefully and to exhume more physics behind
  - low energy
  - model independent

# PKU REPRESENTATION

- Production representation, or PKU representation: elastic two-body scattering amplitude

$$S = \prod_i S_i \times S_{cut}$$

- $S_i$ : pole terms,  $S_{cut} = e^{2i\rho(s)f(s)}$ : left-hand cuts and right hand inelastic cut – background.

$$f(s) = \frac{s}{2\pi i} \int_L ds' \frac{\text{disc}f(s')}{(s' - s)s'} + \frac{s}{2\pi i} \int_{R'} ds' \frac{\text{disc}f(s')}{(s' - s)s'}$$

- $f(0) \equiv 0$  [Z. Y. Zhou and H. Q. Zheng 2006 NPA]

QFT version of Ning Hu representation



Prof. Ning Hu (1916–1997)

- 1943: PhD in Caltech.
- 1942–1945: IAS, Princeton.
- 1945–1947: IAS, Ireland.
- 1947 – 1948: Nils Bohr Institute.
- 1948 – 1950, Cornell U., Wisconsin U..
- 1951 – 1997: Peking University

Theory for meson nucleon interaction;  
General relativity and gravitational wave;  
 $S$  matrix theory;  
Quantum electro dynamics;  
Quark model.

# PKU REPRESENTATION

- $f(s)$  perturbatively calculated, poles as parameters (input or fit)
- Corresponding to the Ning Hu representation in QM

[N. Hu 1948 PR] [T. Regge 1958 Nuovo Cimento]

- Advantages

- rigorous and universal
- separated  $S \rightarrow$  additive phase shift
- sensitive to (not too) distant poles
- definite sign of the phase shifts  $\rightarrow$  figuring out hidden contributions

- Applications

- the  $\pi\pi$  elastic scattering  $\rightarrow$  existence of the  $\sigma$  particle ( $f_0(500)$ )

[Z. G. Xiao and H. Q. Zheng 2001 NPA]

- the  $\pi K$  elastic scattering  $\rightarrow \kappa$  resonance ( $K^*(800)$ )

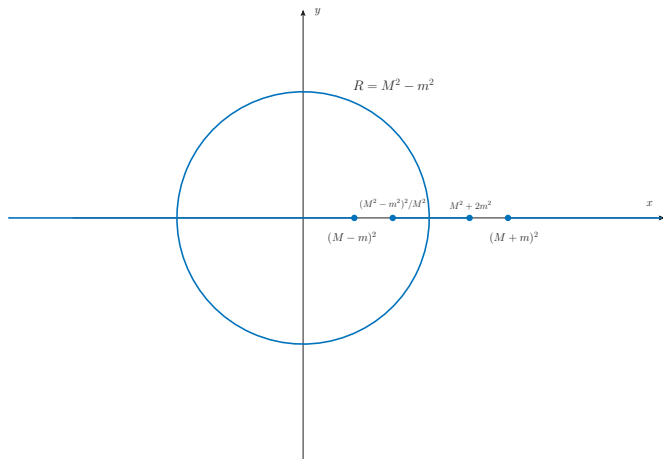
[H. Q. Zheng et. al. 2004 NPA]

- resonance sum rules (narrow width approximation)

[Guo Z.H. et al., JHEP 2007 NPA]

# BRANCH CUT STRUCTURE OF PARTIAL WAVE $\pi N$ ELASTIC SCATTERING AMPLITUDE

[S. W. MacDowell 1959 PR][J. Kennedy and T. D. Spearman 1961 PR]



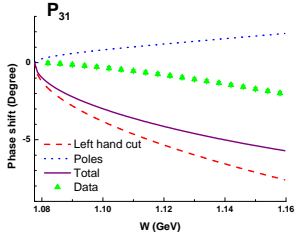
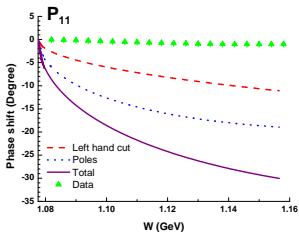
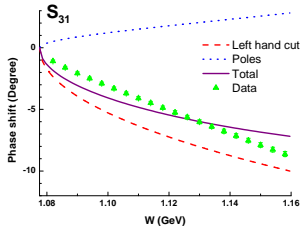
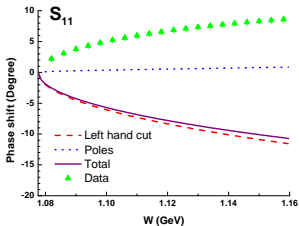
# PHASE SHIFT COMPONENTS

- PKU representation  $\rightarrow$  conventionally additive phase shift
- Phase shift contributions
  - bound states  $\rightarrow$  negative phase shift
  - virtual states (**usually hidden !**)  $\rightarrow$  positive phase shift
  - resonances  $\rightarrow$  positive phase shift
  - left hand cut  $\rightarrow$  (empirically) negative phase shift (proved in quantum mechanical potential scatterings)

[T. Regge 1958 Nuovo Cimento]

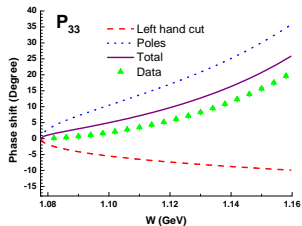
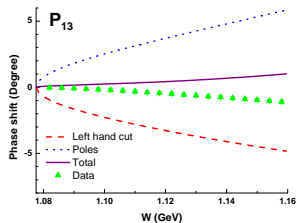
# BACKGROUND PHASE SHIFTS

Estimated both at  $O(p^2)$  and  $O(p^3)$  level. (Tree level plotted).  $L_{2I 2J}$  convention,  $W = \sqrt{s}$ , data: green triangles [SAID: WI 08]



# BACKGROUND PHASE SHIFTS

$L_{2I} 2J$  convention,  $W = \sqrt{s}$ , data: green triangles [SAID: WI 08]

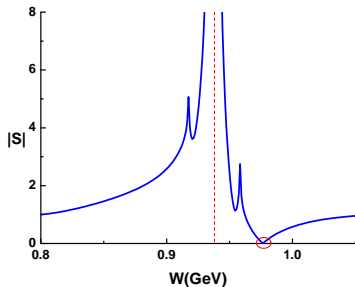


## DISCREPANCIES IN $S_{11}$ AND $P_{11}$ CHANNELS

Large missing positive contributions

$P_{11}$ :

- Analytical continuation:  $S^{\text{II}} = 1/S^{\text{I}}$ .  
Second sheet poles  $\rightarrow$  first sheet zeros.
- Expansion:  $S^{\text{I}} \sim a/(s - M_N^2) + b + \dots$
- Arbitrary non-zero  $b \rightarrow$  the virtual state
- Perturbation calculation  $\rightarrow$  virtual state at 976 MeV; fit  $\rightarrow$  980 MeV



## FINDING $S_{11}$ HIDDEN POLE

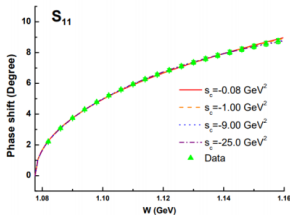
$O(p^2)$  [YF Wang et al., 2018 EPJC];

$O(p^3)$  [YF Wang et al., 2019 CPC]

- Hidden pole  $\rightarrow$  a “crazy resonance” below threshold  $0.895(81)(2) - 0.164(23)(4)i$  GeV.

$s_c$ (GeV <sup>2</sup> )	Pole position (MeV)	$\chi^2/\text{d.o.f}$
-0.08	$814(3) - i 141(8)$	1.46
-1.00	$882(2) - i 190(4)$	1.31
-9.00	$960(2) - i 192(2)$	1.14
-25.0	$976(2) - i 187(1)$	1.14

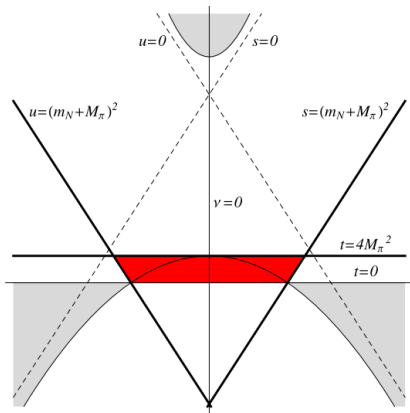
Table 2: The  $S_{11}$  hidden pole fit with different choices of  $s_c$ .



Navigation icons: back, forward, search, etc.

# Positivity constraints for $\pi N$ scatterings

[Sanz-Cillero, Guo ZH, ZHQ, Eur.Phys.J.C 74 (2014) 2763]



**Fig. 1** Mandelstam plane ( $v, t$ ). The Mandelstam triangle is the region contoured by the  $s = (m_N + M_\pi)^2$ ,  $u = (m_N + M_\pi)^2$  and  $t = 4M_\pi^2$  lines. Our region of study  $\mathcal{R}$  is the trapezium formed by the three previous lines and  $t = 0$ , which is marked in red

# Accumulation of Singularities

[Li QZ and ZHQ, Commun. Theor. Phys. 74 (2022) 11, 115203]

## Singularities and Accumulation of Singularities of $\pi N$ Scattering amplitudes

July 18, 2022

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### Abstract

It is demonstrated that for the isospin  $I = 1/2$   $\pi N$  scattering amplitude,  $T^{I=1/2}(s, t)$ ,  $s = (m_N^2 - m_\pi^2)^2/m_N^2$  and  $s = m_N^2 + 2m_\pi^2$  are two accumulation points of poles on the second sheet of complex  $s$  plane, and are hence accumulation of singularities of  $T^{I=1/2}(s, t)$ . For  $T^{I=3/2}(s, t)$ ,  $s = (m_N^2 - m_\pi^2)^2/m_N^2$  is the accumulation point of poles on the second sheet of complex  $s$  plane. The proof is valid up to all orders of chiral expansions.

[A. Martin, F. Cheung, 1970's]

# Roy-Steiner equation

## Roy-Steiner Equation

[Roy 1971]

- A coupled system of PWDRs.
- Analyticity, Unitarity, and Crossing symmetry.

Starting from the twice-subtracted fixed- $t$  dispersion relation:

$$T(s, t, u) = \alpha(t) + s\beta(t) + \frac{s^2}{\pi} \int_{4m_\pi^2}^{\infty} ds' \frac{\text{Im } T(s', t, u')}{s'^2 (s' - s)} + \frac{s^2}{\pi} \int_{-\infty}^{-t} ds' \frac{\text{Im } T(s', t, u')}{s'^2 (s' - s)}, \quad (1)$$

A system of integral equations for the  $\pi\pi$  amplitudes:

$$\text{Re } t_J^I(s) = k_J^I(s) + \sum_{I'} \sum_{J'} \int_{4m_\pi^2}^{\infty} ds' K_{JJ'}^{II'}(s', s) \text{Im } t_{J'}^{I'}(s'). \quad (2)$$

- $K_{JJ'}^{II'}(s', s)$ : Analytically calculable kinematic kernel functions.
- The only free parameters:  $S$ -wave scattering lengths  $a_0^0, a_0^2$ .

**An important issue is the range of validity of the Roy equations.**

## Roy-Steiner equation



**Shasanka Mohan Roy**   **Frank Steiner**

## Lehmann ellipse constraints

$$\text{Im}_s T(s', t) = 16\pi \sum_l (2l+1) \text{Im}_s T_l(s') P_l(z(s', t)) , \quad (3)$$

$z$ : **CMS scattering angle cosines.**

The series of Legendre polynomials converges when  $z$  within the corresponding large Lehmann ellipses [Lehmann 1958].

### Lehmann ellipses

- Focal points:  $z = \pm 1$ .
- Boundary: Touching the nearest singularity of  $\text{Im}_s T(s', t)$ .

Assuming that the scattering amplitude satisfies Mandelstam' s double spectral representation.

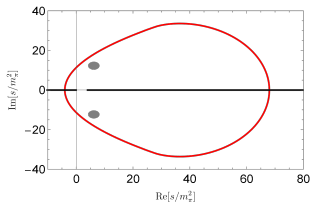


Figure: Domain of validity of the Roy Equation; black points denote the  $\sigma(f_0(500))$ .

Similarly, for  $\pi K$  and  $\pi N$  scattering amplitudes:

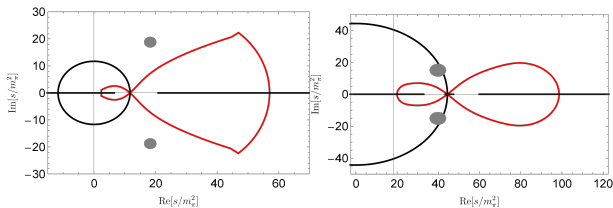


Figure: Left:  $\pi K$  systems, points denote the  $\kappa(K_0^*(700))$ ; Right:  $\pi N$  systems, points denote the  $N^*(890)$

Roy equation (fixed- $t$  dispersion relation ): unfit to search for a wide resonance.

Using the hyperbolic dispersion relations, One can get the Roy-Steiner equations, which looks like:

$$\begin{aligned} \operatorname{Re} f_l(s) &= N_l(s) + \sum_{l'} \int_{s_{th}} ds' K_{l,l'}(s, s') \operatorname{Im} f_l(s') + \sum_J \int_{t_{th}} dt' G_{l,J}(s, t') \operatorname{Im} g(t')_J, \\ \operatorname{Re} g_J(t) &= \tilde{N}_J(t) + \sum_{l'} \int_{s_{th}} ds' \tilde{K}_{J,l'}(t, s') \operatorname{Im} f_l(s') + \sum_{J'} \int_{t_{th}} dt' \tilde{G}_{J,J'}(t, t') \operatorname{Im} g(t')_{J'}. \end{aligned} \quad (4)$$

- $f_l(s)$ : s-channel PWAs;
- $g_J(t)$ : t-channel PWAs;
- $N, K, G$ : Analytically calculable kinematic kernel functions.

## RS equation analysis of $\pi N$ scatterings

RS equation has been applied to study  $\pi N$  scatterings [Ditsche:2012, Hoferichter:2015].

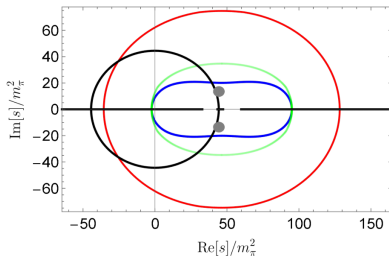


FIG. 2: Validity domain of the fixed- $b$  RS representation ( $a = 0$ ). The blue and green lines correspond to the boundaries in the  $s'$  and  $t'$  integrals associated with  $\rho_{st}$ , respectively. The red line corresponds to the boundaries in the  $s'$  integral associated with  $\rho_{su}$ .

[Cao XH, Li QZ, HQZ, JHEP 12 (2022) 073].

- $S_{11}$ :  $\sqrt{s} = 919 \pm 4 - (162 \pm 7)i$   $N^*(920)$ .
- $P_{33}$ :  $\sqrt{s} = 1213 \pm 2 - (50 \pm 3)i$   $\Delta(1232)$ .

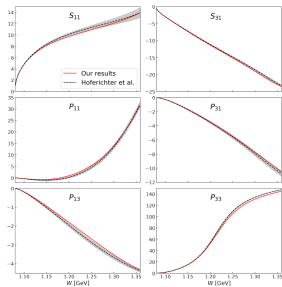
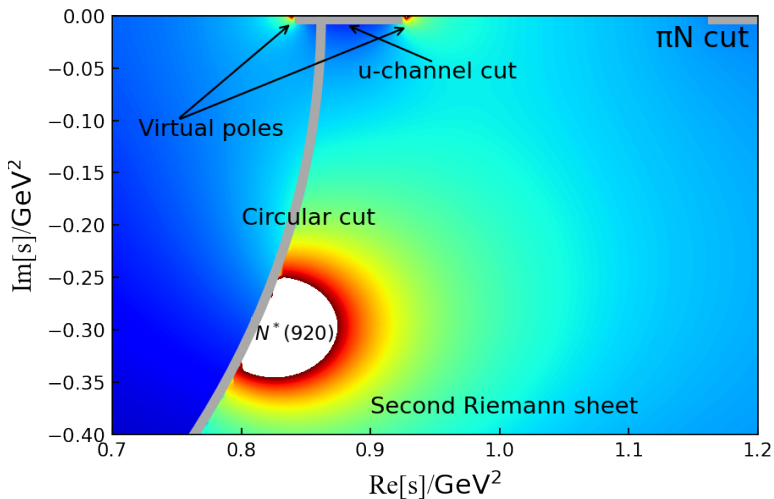
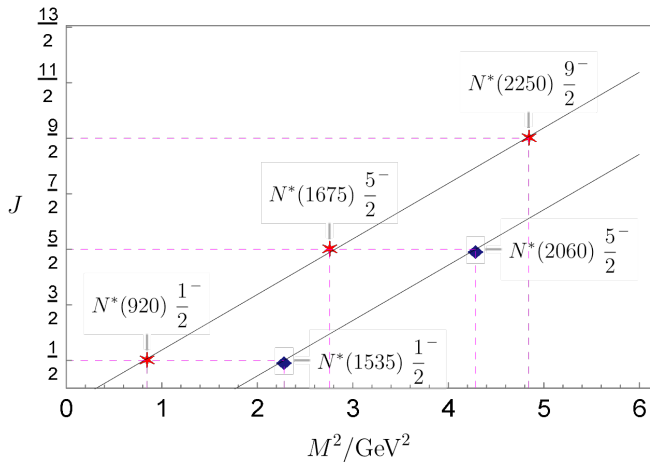


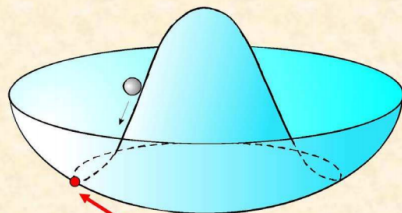
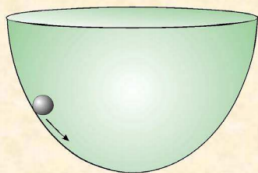
FIG. 3: Phase shifts of the  $s$ -channel PWs from our solutions (solid line) and [10] (dashed line with error bands) in the low-energy region. The deviation of  $P_{33}$  phase shift comes from the difference between values of GWU/SAID and [10] at the matching point ( $W_m = 1.36$  GeV), and they differ by about  $2^\circ$ .



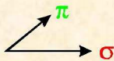
# Regge Trajectory



# Ground State – Vacuum



Chiral symmetry breaking



M.R. Pennington, YKIS06

# The linear sigma model

## The linear sigma model

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_s + c\sigma, \\ \mathcal{L}_s &= \frac{1}{2}[(\partial_\mu\sigma)^2 + (\partial_\mu\pi)^2] + \frac{m^2}{2}[\sigma^2 + \pi^2] - \frac{\lambda}{4}[\sigma^2 + \pi^2]^2, \quad (1)\end{aligned}$$

when  $c \rightarrow 0$ , the lagrangian is invariant under  $SU_L(2) \times SU_R(2)$  chiral rotations

$$\begin{aligned}\vec{\pi} &\rightarrow \vec{\pi} + \vec{\alpha} \times \vec{\pi} - \vec{\beta}\sigma, \\ \sigma &\rightarrow \sigma + \vec{\beta} \cdot \vec{\pi}\end{aligned} \quad (2)$$

Weinberg's  
"Folk Theorem"



If one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible  $S$ -matrix consistent with analyticity, perturbative unitarity, cluster decomposition, and the assumed symmetry principles.

*Physica* **96A**, 327 (1979)

## To be or not to be, this is a question

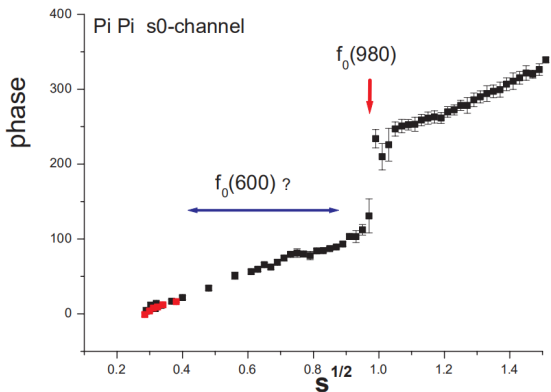
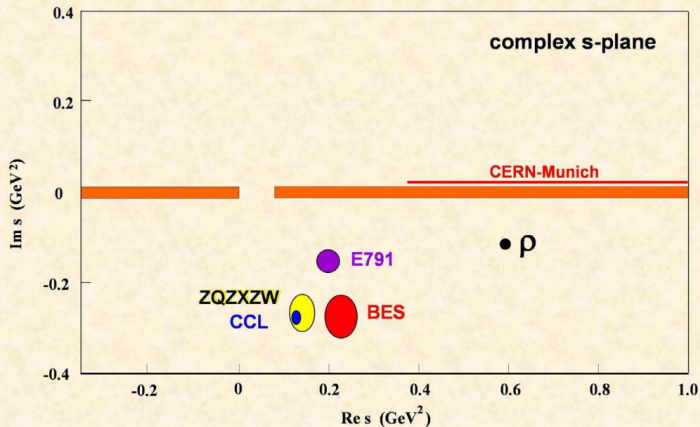


Figure:  $IJ=00$  channel  $\pi\pi$  scattering phase shift data from CERN-Munich and E865.

$$\pi\pi : I = 0, J = 0$$



Zhou, Qin, Zhang, Xiao, Zheng & Wu

Caprini, Colangelo, & Leutwyler

M.R. Pennington, YKIS06

# $\pi\pi$ phase shift at un-physical pion masses

[Cao XH, Li QZ, Guo ZH, HQZ, Phys.Rev.D 108 (2023) 3, 034009]

## Modified Roy equations; Lattice data

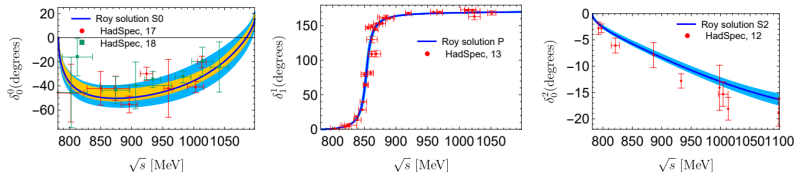


FIG. 6.  $\pi\pi$  phase shifts at  $m_\pi = 391$  MeV from Roy equation solutions: S0, P and S2 stand for the results of the  $IJ = 00, 11, 20$  channels, respectively. For the sources of the shaded error bands, see the main text for details. The lattice data are taken from Refs. [24–26, 28].

$$a_0^0 = -(3.8_{-1.2}^{+1.1}), \quad a_0^2 = -(0.21_{-0.03}^{+0.02}),$$

$$\sqrt{s_\sigma} = 759_{-16}^{+7} \text{ MeV}, \quad |g_{\sigma\pi\pi}| = 493_{-46}^{+27} \text{ MeV}.$$

# $\pi\pi$ phase shift at un-physical pion masses

[Cao XH, Li QZ, Guo ZH, HQZ, Phys.Rev.D 108 (2023) 3, 034009]

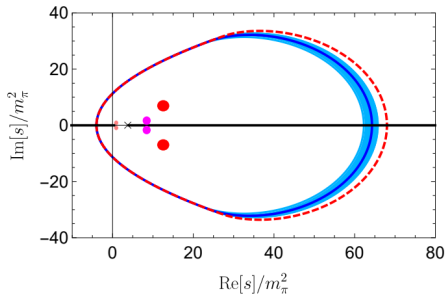


FIG. 7. Validity domain of extended Roy equation for  $m_\pi = 391$  MeV. The dashed red boundary represents the validity domain by dropping the effects of the bound state  $\sigma$ , and the blue boundary corresponds to the complete validity domain within uncertainty from the location of the  $\sigma$ . The poles in the validity domain in the second RS are from left to right, as shown in Eq. (15).

## $\pi\pi$ phase shift at un-physical pion masses

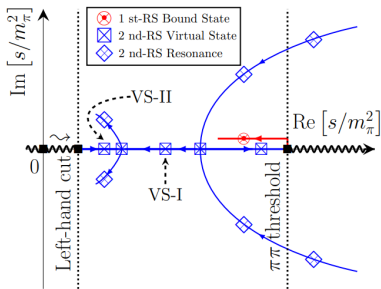


FIG. 9. The qualitative trajectory of the  $\sigma$  pole on the second RS of the  $s$  plane with varying  $m_\pi$ . See the main text for the meaning of the labels ‘VS-I,II’.

# O(N) $\sigma$ model revisited at different pion masses

[Lyu YL, Li QZ, Xiao ZG, HQZ, Phys.Rev.D 109 (2024) 9, 094026; ibid 110 (2024) 9, 094054]

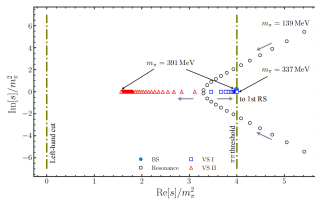


Figure: Large N method. Pole position with respect to different  $m_\pi$ .

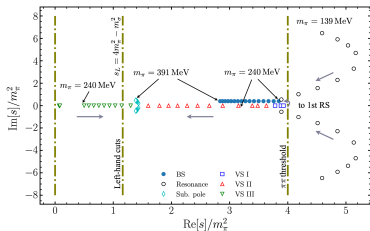


Figure: N/D improved. Pole position with respect to different  $m_\pi$ .

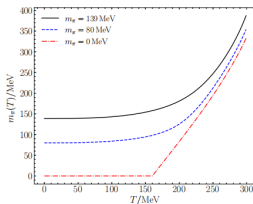
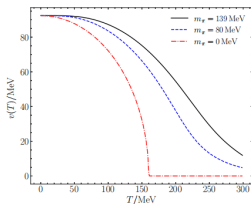
# O(N) $\sigma$ model revisited at different temperatures

- The leading order effective potential at finite temperature  $T$  can be obtained with imaginary time formalism [M. L. Bellac, *Thermal Field Theory*, CUP 2011] by Wick rotation to Euclidean space and substituting the momentum integral with a sum over Matsubara frequencies  $\omega_n = 2\pi nT$ , i.e.  $\int \frac{d^4k}{(2\pi)^4} f(k_0, \mathbf{k}) \rightarrow iT \sum_n \int \frac{d^3\mathbf{k}}{(2\pi)^3} f(k_0 = i\omega_n, \mathbf{k})$ .
- By minimizing the effective potential, we can obtain the gap equations for  $v$  and  $m_\pi^2$  as functions of temperature [J. O. Andersen, D. Boer, and H. J. Warringa, PRD 2004] :

$$v^2(T) = f_\pi^2 + \frac{N}{16\pi^2} \left( m_\pi^2 \log \frac{m_\pi^2}{M^2} - m_\pi^2(T) \log \frac{m_\pi^2(T)}{M^2} \right) - NA^{T \neq 0} (m_\pi^2(T), T)$$

$$\alpha = v(T)m_\pi^2(T)$$

where  $v(0) = f_\pi$  and  $m_\pi(0) = m_\pi$  are set to zero-temperature values.



# $O(N)$ $\sigma$ model revisited at different temperatures

- The  $I = J = 0$  channel scattering amplitude at LO  $1/N$  expansion with finite temperature is obtained as,

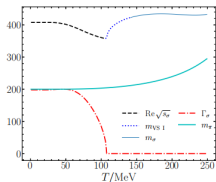
$$\mathcal{T}_{00}^T(s) = -\frac{1}{32\pi} \frac{s - m_\pi^2(T)}{(s - m_\pi^2(T)) B^T(s, m_\pi(T), M) - v^2(T)/N},$$

where the finite temperature effect introduced by loop diagrams can be standardly calculated as

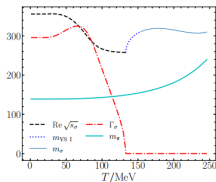
$$B^T(s, m_\pi(T), M) = B(s, m_\pi(T), M) + B^{T \neq 0}(s, m_\pi(T), T),$$

$$B^{T \neq 0}(s, m_\pi(T), T) = \int_0^\infty \frac{dk k^2}{8\pi^2 \omega_k^2} n_B(\omega_k) \left( \frac{1}{E + 2\omega_k} - \frac{1}{E - 2\omega_k} \right),$$

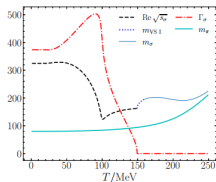
with  $\beta = 1/T$ ,  $\omega_k = \sqrt{k^2 + m_\pi^2(T)}$  and  $n_B(\omega_k) = (e^{\beta\omega_k} - 1)^{-1}$  is the Bose-Einstein distribution.  $B^{T \neq 0}$  is evaluated in the CM frame and  $s = E^2$ .



$m_\pi = 200$  MeV



$m_\pi = 139$  MeV



$m_\pi = 80$  MeV

# N/D improved calculations

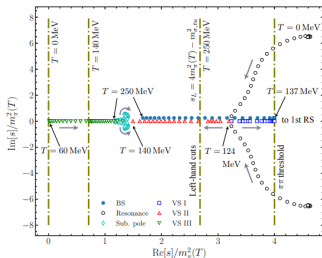
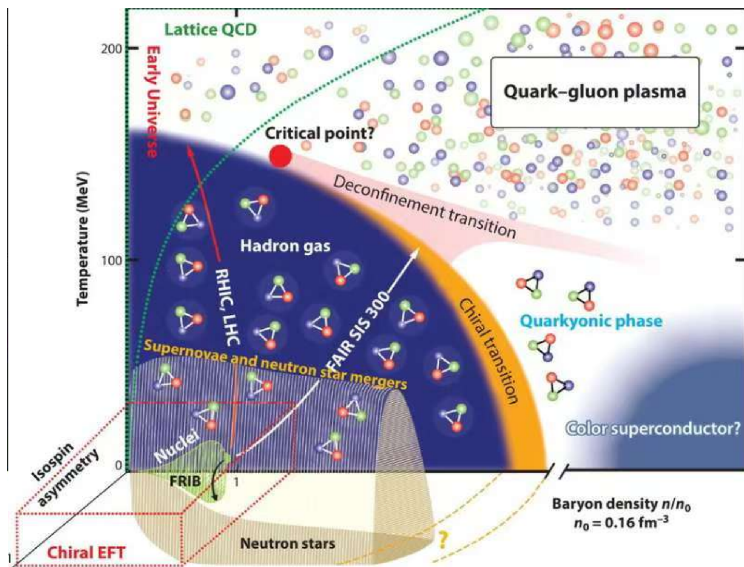
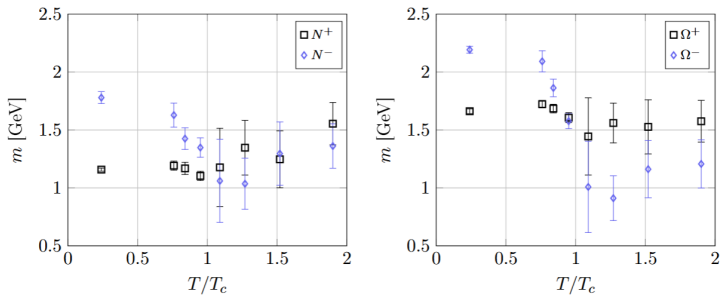


FIG. 16. The thermal  $\sigma$  pole trajectory obtained in  $N/D$  modified  $O(N)$  model. The zero-temperature pion mass is set as  $m_\pi(0) = 139$  MeV. When the temperature increases, similar to the leading order result [18],  $\sigma$  turns into two virtual states (VS I&II) and then becomes a bound state (BS) after VS I moves towards and across the threshold to the first Riemann sheet (RS). The left-hand cut branch point extends to  $s_L = 4m_\pi^2(T) - m_{\sigma,tu}^2$  due to the  $\sigma$  exchange in crossed channels. Additionally, the third virtual state pole (VS III) generated close to  $s_L$  will meet VS II on the real axis, then becoming a pair of subthreshold (Sub.) poles and going into the complex plane. Finally, the pair of subthreshold poles tends to  $s_A = m_\pi^2(T)$  as  $T \gg T_c$ .

# Temperature properties of $N^*(920)$





**Figure 3.** Groundstate masses in the positive- and negative-parity channels at *all* temperatures, assuming the exponential decay of Eq. (4.2), in the  $N$  (left) and  $\Omega$  (right) channels.

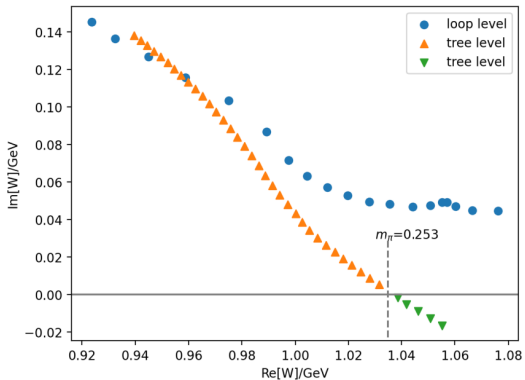
$T_c = 185\text{MeV}$ ; [G. Aarts et al., JHEP 06 (2017)]

$N^*(920)$ ?!

# Properties of $N^*(920)$

[ Qu-Zhi Li, ZG Xiao, HQZ, Chin.Phys. 49 (2025) 12, 123103]

Figure: Pole trajectory of  $N^*(920)$  with varying  $m_\pi$



Temperature Properties: In Progress!

# Spontaneous symmetry breaking

If the ground state of QCD (=hadron spectrum) has the same symmetry as the Lagrangian (namely, chiral symmetry), then “parity doublets” exist; because:

Let  $|i, +\rangle$  denote an eigenstate of  $H_{\text{QCD}}^0$  with eigenvalue  $E_i$ ,

$$H_{\text{QCD}}^0|i, +\rangle = E_i|i, +\rangle,$$

having positive parity,

$$P|i, +\rangle = +|i, +\rangle,$$

such as, e.g., a member of the ground state baryon octet (in the chiral limit).

Defining  $|\phi\rangle = Q_A^a|i, +\rangle$ , because of  $[H_{\text{QCD}}^0, Q_A^a] = 0$ , we have

$$H_{\text{QCD}}^0|\phi\rangle = H_{\text{QCD}}^0 Q_A^a|i, +\rangle = Q_A^a H_{\text{QCD}}^0|i, +\rangle = E_i Q_A^a|i, +\rangle = E_i|\phi\rangle,$$

i.e., the new state  $|\phi\rangle$  is also an eigenstate of  $H_{\text{QCD}}^0$  with the same eigenvalue  $E_i$  but of opposite parity:

$$P|\phi\rangle = P Q_A^a P^{-1} P|i, +\rangle = -Q_A^a(+|i, +\rangle) = -|\phi\rangle.$$

### Spontaneous symmetry breaking, cont'd

What would parity doublets look like?

Nucleons of positive parity:  $p(1/2^+, 938.3)$ ,  $n(1/2^+, 939.6)$ ,  $I=1/2$ ;

nucleons of negative parity:  $N(1/2^-, 1535)$ ,  $I=1/2$ .

But, the masses are very different: **NOT** a parity doublet!

A meson of negative parity:  $\rho(1^-, 770)$ ,  $I=1$ ,

the "same" with positive parity:  $a_1(1^+, 1260)$ ,  $I=1$ .

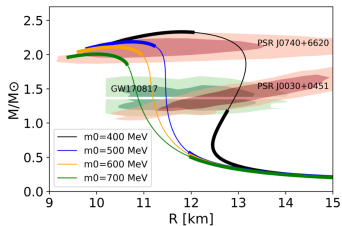
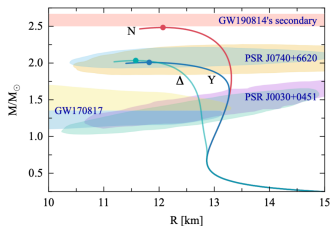
But again, the masses are very different: **NOT** a parity doublet!

Conclusion: Parity doublets are **not** observed in the low-energy hadron spectrum.



Chiral symmetry is **spontaneously** broken.

# Neutron Star



[T. Minamikawa, B. Gao, T. Kojo, and M. Harada, *Symmetry* 15, 745 (2023)]

## Conclusions and Perspectives

- ① There exists a spin one half, negative parity sub-threshold nucleon pole.
- ②  $\sigma$  becomes a bound state pole at large  $m_\pi$  and high temperature.
- ③ Parity doublet model!? EOS Neutron star?

Final goals: fully understanding the role of  $N^*(920)$

— Thanks for patience!