Light molecular mesons with exotic and ordinary quantum numbers

Feng-Kun Guo

Institute of Theoretical Physics, Chinese Academy of Sciences

Mao-Jun Yan, Jorgivan Dias, Adolfo Guevara, FKG, Bing-Song Zou, Universe 9, 109 (2023);
Mao-Jun Yan, Jorgivan Dias, FKG, Bing-Song Zou, in preparation

Light mesons with exotic quantum numbers

- Light meson resonances with $J^{PC} = 1^{-+}$: isovector candidates

PDG 2024

$\pi_1(1400)$ $I^G(J^{PC}) = 1^-(1^{-+})$

Coupled channel analyses favor the existence of only one broad 1^{-+} isovector state consistent with $\pi_1(1600)$ in the $1400 - 1600$ MeV region. See the review on "Spectroscopy of Light Meson Resonances". See also $\pi_1(1600)$.

$\pi_1(1600)$ $I^G(J^{PC}) = 1^-(1^{-+})$

Coupled channel analyses favor the existence of only one broad 1^{-+} isovector state consistent with $\pi_1(1600)$ in the $1400 - 1600$ MeV region. Accordingly, the $\pi_1(1400)$ entries of the previous Reviews have been moved into this section. See the review on "Spectroscopy of Light Meson Resonances."

$\pi_1(1600)$ T-Matrix Pole $\sqrt{s}$	$(1480 - 1680) - i(150 - 300)$ MeV
$\pi_1(1600)$ MASS ($\eta\pi$ mode)	1354 ± 25 MeV (S = 1.8)
$\pi_1(1600)$ MASS (non-$\eta\pi$ mode)	1645^{+40}_{-17} MeV (S = 1.3)
$\pi_1(1600)$ WIDTH ($\eta\pi$ mode)	330 ± 35 MeV
$\pi_1(1600)$ WIDTH (non-$\eta\pi$ mode)	370^{+50}_{-60} MeV

$\pi_1(1600)$ DECAY MODES

	Mode
Γ_1	$\pi\pi\pi$
Γ_2	$\rho^0\pi^-$
Γ_3	$f_2(1270)\pi^-$
Γ_4	$b_1(1235)\pi$
Γ_5	$\eta'(958)\pi^-$
Γ_6	$\eta\pi$
Γ_7	$f_1(1285)\pi$

Light mesons with exotic quantum numbers

- Light meson resonances with $J^{PC} = 1^{-+}$: isoscalar candidate

$\eta_1(1855)$ $I^G(J^{PC}) = 0^+(1^{-+})$

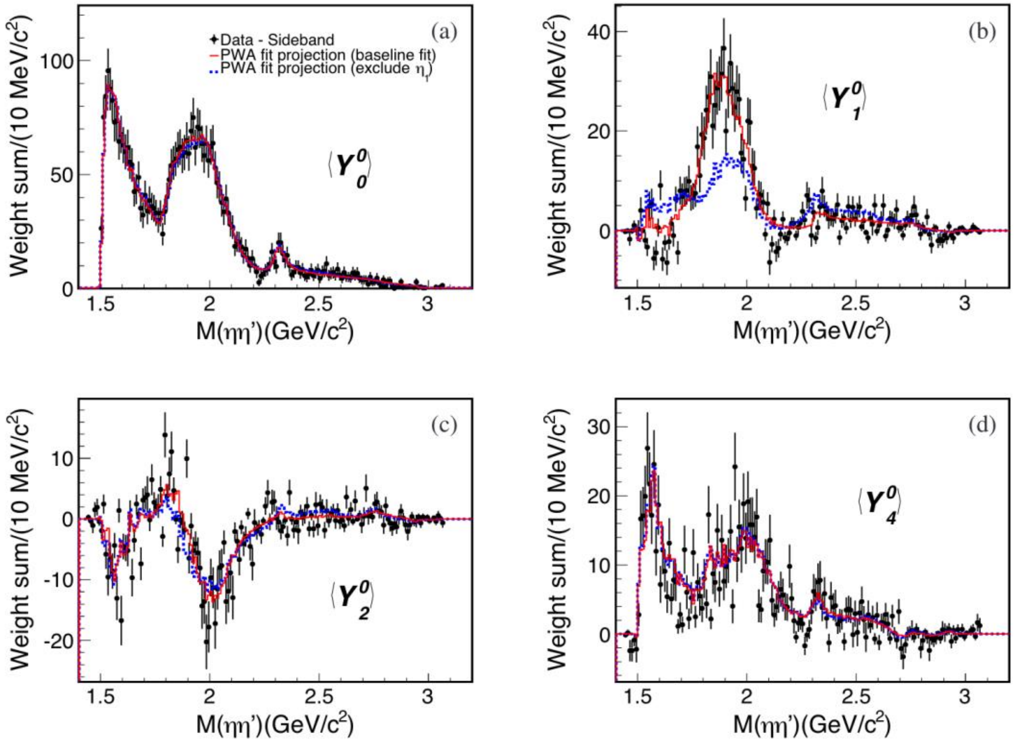
PDG 2024

Meson with exotic (non-$q\bar{q}$) quantum numbers. A state decaying into $\eta\eta'$ with possible quantum numbers 1^{-+} was reported earlier in this mass region BARBERIS 2000A in high energy central pp production and by ALDE 1991B in $\pi^- p$ interactions, see the $f_2(1910)$, and the review on "Spectroscopy of Light Meson Resonances."

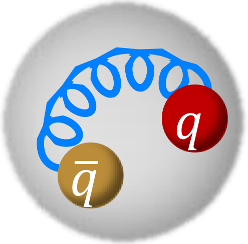
$\eta_1(1855)$ MASS	1855^{+11}_{-9} MeV
$\eta_1(1855)$ WIDTH	188 ± 19 MeV

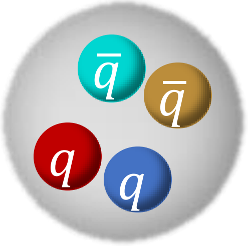
$\eta_1(1855)$ **DECAY MODES**

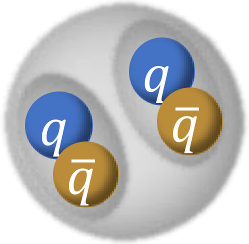
	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\eta\eta'$	seen		528



  - Observed by BESIII in $J/\psi \to \gamma\eta\eta'$ BESIII, PRL 129, 192002 (2022)
- Often considered as hybrid mesons (with gluonic excitations)
  - But $q\bar{q}$ can be produced through the "constituent" gluon
  - Are the hybrid mesons equivalent to tetraquarks/hadronic molecules?







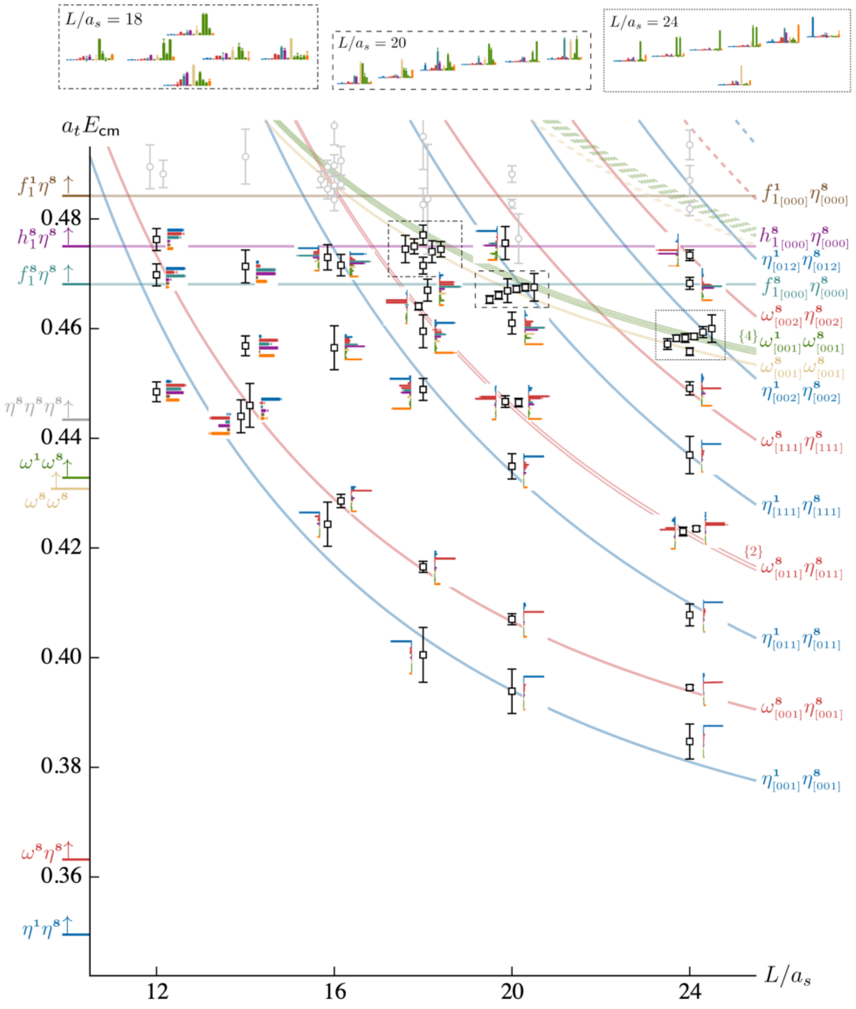
Light mesons with exotic quantum numbers

- Lattice QCD calculation of the $J^{PC} = 1^{-+}$ isovector π_1 resonance (SU(3) sym. $M_\pi \approx 700$ MeV):
  - Considered single-meson and meson-meson operators
  - Luescher's method: FV energy levels ⇒ parametrized T matrix
  - Pole and residues
    - Dominantly couple to $b_1\pi$

HadSpec, PRD 103, 054502 (2021)

TABLE VIII. Thresholds, couplings and partial widths for each channel kinematically open at $m_R = 1564$ MeV. Couplings are derived as discussed in the text and partial widths are determined according to the definition given in Eq. (13). For both couplings and partial widths we present a range calculated from the corresponding SU(3) couplings, while those shown as an upper bound have a preferred value of zero.

	Thr./MeV	$\lvert c_i^{\rm phys}\rvert$/MeV	Γ_i/MeV
$\eta\pi$	688	$0 \to 43$	$0 \to 1$
$\rho\pi$	910	$0 \to 203$	$0 \to 20$
$\eta'\pi$	1098	$0 \to 173$	$0 \to 12$
$b_1\pi$	1375	$799 \to 1559$	$139 \to 529$
$K^*\bar{K}$	1386	$0 \to 87$	$0 \to 2$
$f_1(1285)\pi$	1425	$0 \to 363$	$0 \to 24$
$\rho\omega\{^1P_1\}$	1552	$\lesssim 19$	$\lesssim 0.03$
$\rho\omega\{^3P_1\}$	1552	$\lesssim 32$	$\lesssim 0.09$
$\rho\omega\{^5P_1\}$	1552	$\lesssim 19$	$\lesssim 0.03$
$f_1(1420)\pi$	1560	$0 \to 245$	$0 \to 2$
			$\Gamma = \sum_i \Gamma_i = 139 \to 590$



Light mesons with ordinary quantum numbers: a_1

- Axial-vector mesons

$a_1(1260)$ $\quad I^G(J^{PC}) = 1^-(1^{++})$

See also our review under the $a_1(1260)$ in PDG 2006, Journal of Physics G33 1 (2006).

$a_1(1260)$ T-MATRIX POLE $\sqrt{s}$	$(1209^{+13}_{-10}) - i(288^{+45}_{-12})$ MeV
$a_1(1260)$ MASS	1230 ± 40 MeV
$a_1(1260)$ WIDTH	250 to 600 MeV
$D-wave/S-wave$ AMPLITUDE RATIO IN DECAY OF $a_1(1260) \to \rho\pi$	-0.062 ± 0.020 (S = 2.3)

$h_1(1415)$ $\quad I^G(J^{PC}) = 0^-(1^{+-})$

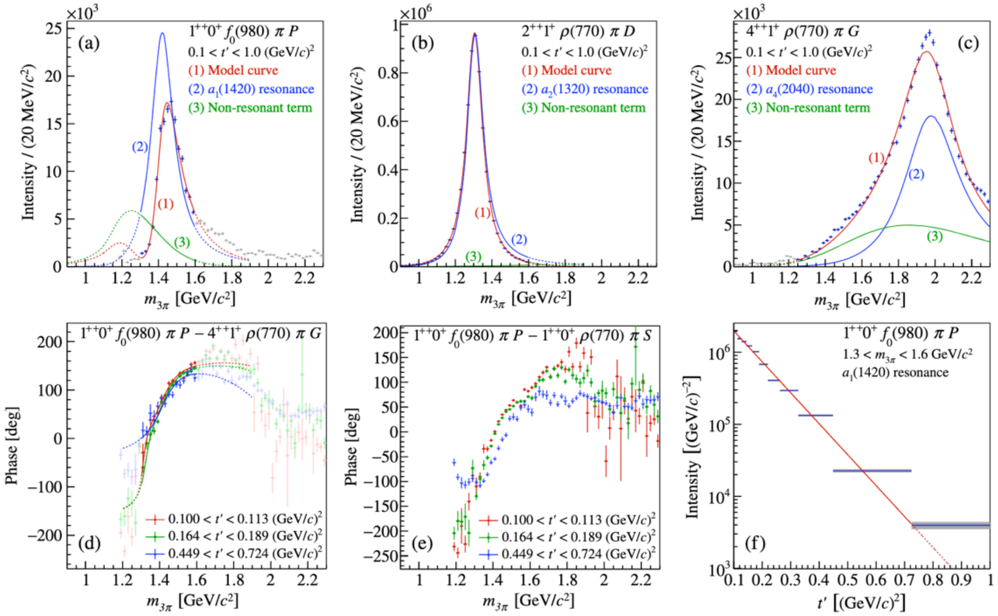
$h_1(1415)$ MASS	1409^{+9}_{-8} MeV (S = 1.9)
$h_1(1415)$ WIDTH	78 ± 11 MeV

$f_1(1420)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$

See the review on "Spectroscopy of Light Meson Resonances."

$f_1(1420)$ MASS	$1428.4^{+1.5}_{-1.3}$ MeV (S = 1.8)
$f_1(1420)$ WIDTH	56.7 ± 3.3 MeV (S = 1.3)

- ☐ $a_1(1420)$ reported by COMPASS in PWA of 3π



So far observed only in the $f_0(980)\pi$ P-wave

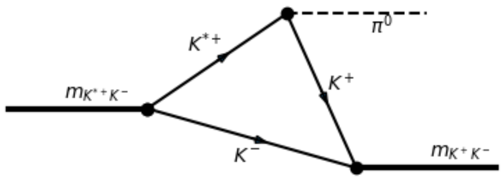
COMPASS, PRL 115, 082001 (2015)

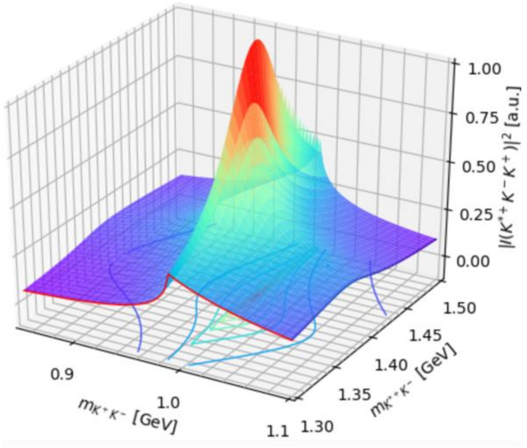
Light mesons with ordinary quantum numbers: a_1

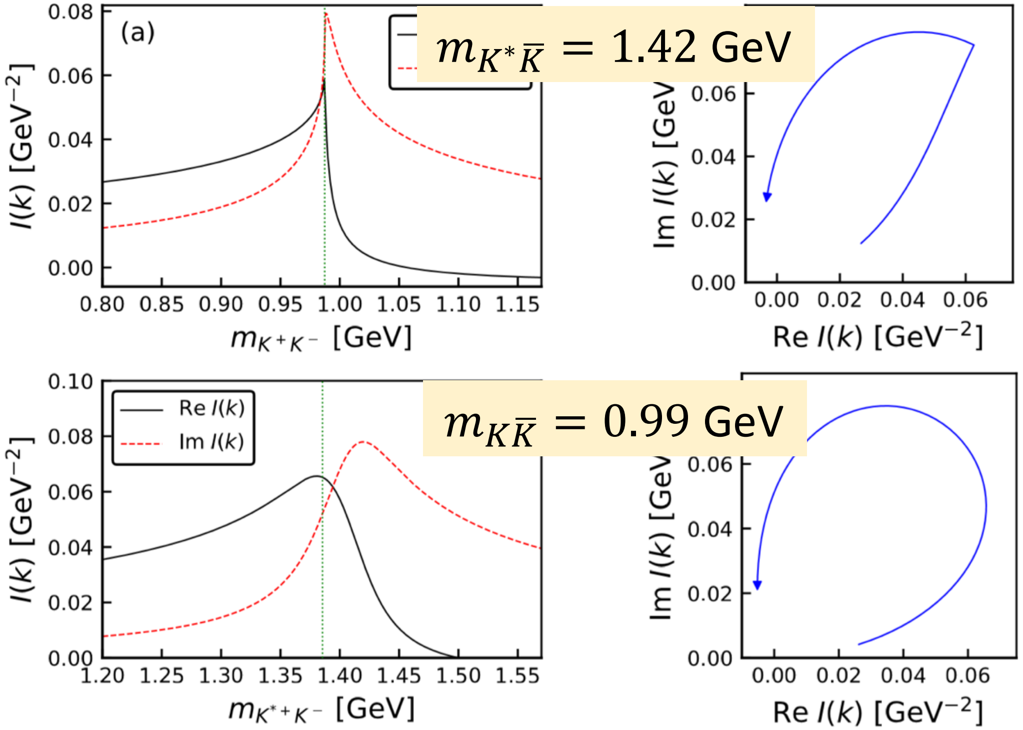
- The $a_1(1420)$ data can also be explained by triangle singularity
  - First suggested by Qiang Zhao @HADRON2013 where the COMPASS data were first reported

M. Mikhasenko, B. Ketzer, A. Sarantsev, PRD 91, 094015 (2015);

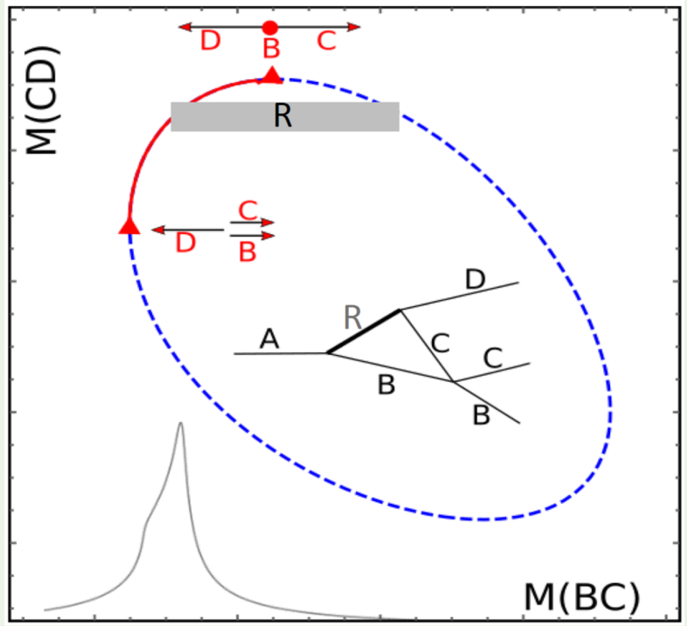
F. Aceti, L.R. Dai, E. Oset, PRD 94, 096015 (2016); …







FKG, X.-H. Liu, S. Sakai, PPNP 112, 103757 (2020)



$p_{B,\text{left}} = p_{B,\text{right}}$

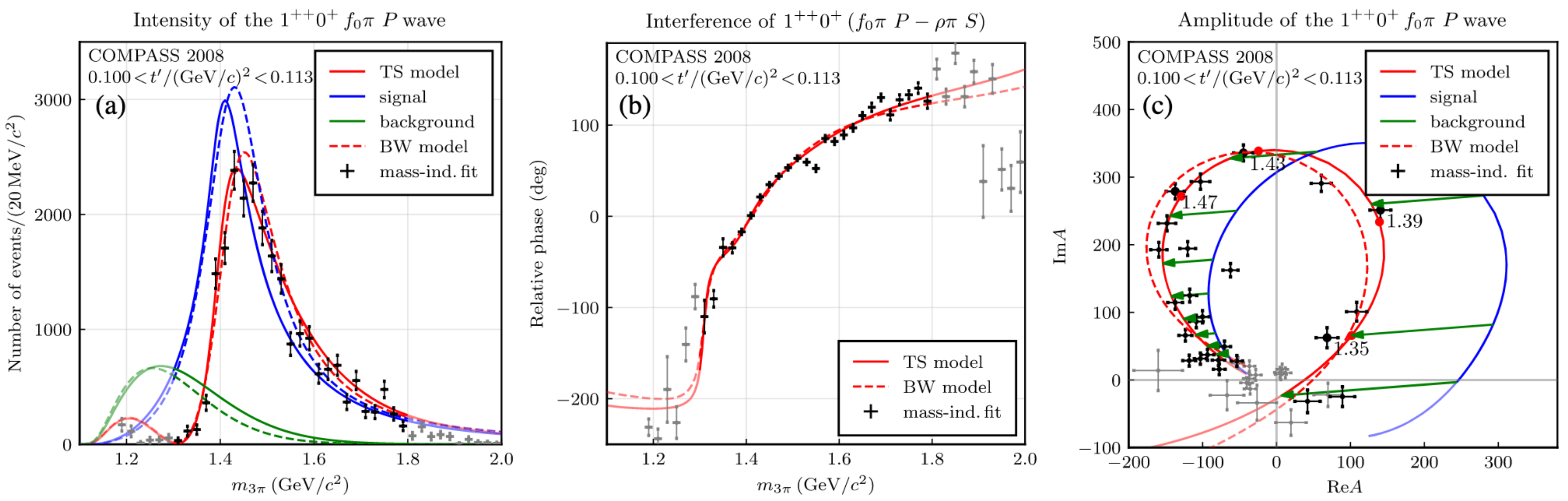
M. Bayar, F. Aceti, FKG, E. Oset, PRD 94, 074039 (2016)

For a review, see FKG, X.-H. Liu, S. Sakai, PPNP 112, 103757 (2020)

Light mesons with ordinary quantum numbers: a_1

- Data cannot distinguish between triangle singularity and genuine resonance for $a_1(1420)$

COMPASS, PRL 127, 082501 (2021)



- **Comment:** should select S-wave $\pi\pi$ events outside the $f_0(980)$ mass region to avoid large contamination from triangle singularity effects
- **Question:** even if there are TS effects, should there still be a resonance around 1.42 GeV?

Kaonic bound states

- Notice S-wave thresholds: $M_{a_1(1420)} \sim M_{K^*} + M_K$, $M_{\eta_1(1855)} \sim M_{K_1(1420)} + M_K$

Nambu-Goldstone boson (NGB)

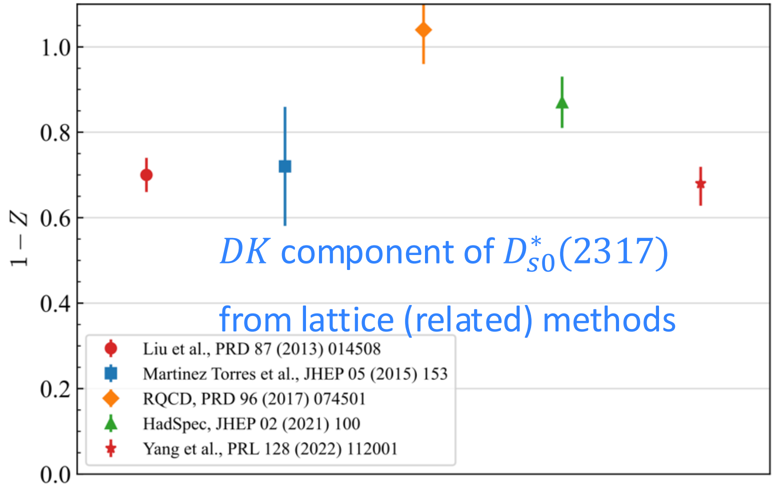
- Chiral symmetry ⇒ Universal leading-order S-wave interaction between kaon and matter field H (pointlike at low energies), the Weinberg-Tomozawa (WT) term

$$V(s) = C_{\rm WT} \frac{M_H E_K(s)}{F_\pi^2}$$

$C_{\rm WT}$ depends on the SU(3) irrep — See, e.g., Hyodo, Jido, Hosaka, PRL 97, 192002 (2006)

Consider HK scattering w/ $I = 1/2$ hadron H in octet: $C_{\rm WT}^{I=0} = -3$, $C_{\rm WT}^{I=1} = -1$

- Many hadronic molecular candidates formed by kaon and isospin-1/2 hadrons (isoscalar: bound; isovector: virtual):
  - The higher pole of $\Lambda(1405)$: $N\bar{K}$ — Dalitz, Tuan, Oller, Meißner, Jido, Oset, Ramos, Hyodo, …
  - $D_{s0}^*(2317)$ & $D_{s1}(2460)$: DK & D^*K — Barnes, Close, Lipkin, van Beveren, Rupp, Chen, Li, Kolomeitsev, Lutz, FKG, Shen, Chiang, Zou, Hanhart, Meißner, Nieves, Oset, …
  - $D_{s1}^*(2860)$: $D_1(2420)K$ — FKG, Meißner, PRD 84, 014013 (2011)
  - $f_0(980)$, $a_0(980)$: $K\bar{K}$ (though NGB pairs) — Isgur, Weinstein, Close, Oller, Oset, Pelaez, Baru, Hanhart, …
  - …
  - Expecting kaonic molecules with $1^{+\pm}$ and $1^{-\pm}$
    - Bound for isoscalar, virtual for isovector



1^{-+} kaonic molecules and partners

- Consider 1^{-+} exotic mesons, couple to S-wave channels:

$\eta_1(1855)$?

Table 1. $J^{PC} = 1^{-+}$ meson-meson channels with $I = 0$. The threshold masses are in the units of MeV.

Channel	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
Threshold	1368	1748	1829	1898	1973

Table 2. $J^{PC} = 1^{-+}$ meson–meson channels with $I = 1$. The threshold masses are in the units of MeV.

Channel	$b_1\pi$	$f_1(1285)\pi$	$f_1(1420)\pi$	$K_1(1270)\bar{K}$	$a_1\eta$	$K_1(1400)\bar{K}$
Threshold	1367	1419	1564	1748	1777	1895

$\pi_1(1400)$?

Table 3. $J^P = 1^-$ meson–meson channels with $I = 1/2$. The threshold masses are in the units of MeV. Here the flavor-neutral axial vector mesons have $J^{PC} = 1^{++}$.

Channel	a_1K	$f_1(1285)K$	$K_1(1270)\eta$	$f_1(1420)K$	$K_1(1400)\eta$
Threshold	1725	1777	1800	1921	1947

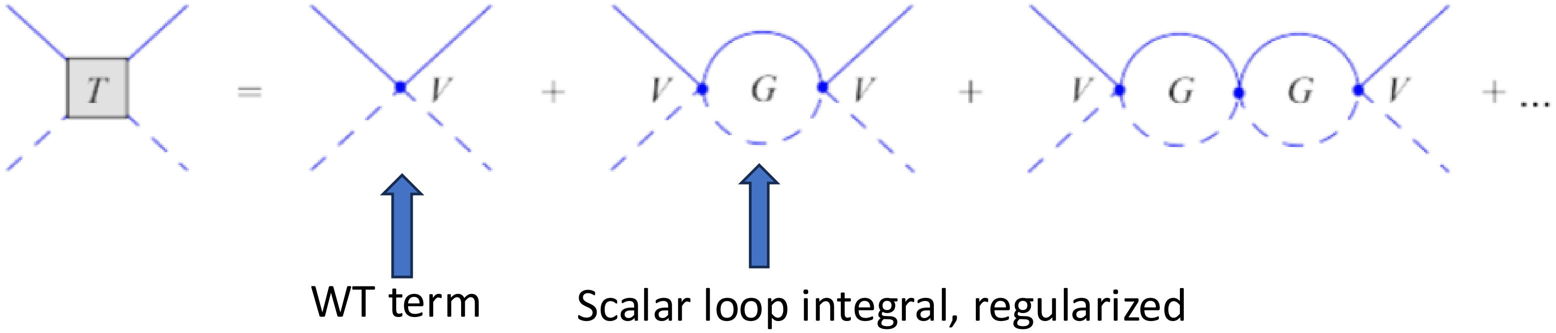
Table 4. $J^P = 1^-$ meson–meson channels with $I = 1/2$. The threshold masses are in the units of MeV. Here, the flavor-neutral axial vector mesons have $J^{PC} = 1^{+-}$.

Channel	$h_1(1170)K$	b_1K	$K_1(1270)\eta$	$h_1(1415)K$	$K_1(1400)\eta$
Threshold	1661	1725	1800	1911	1947

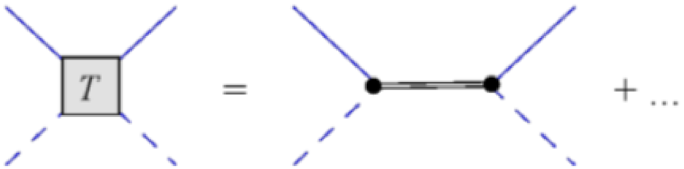
- WT interaction $\propto E_{\mathrm{NGB}}$
- Pion is lighter than kaon, thus weaker interaction; instead of bound states, one gets resonances

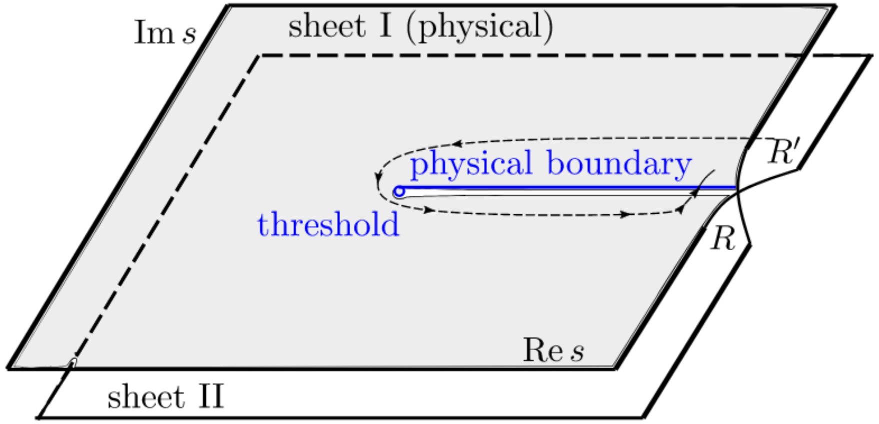
1^{-+} kaonic molecules and partners

- S-wave scattering between NGBs (π, K, η) and 1^{+} light mesons (as matter fields)
  - Use chiral unitary approach — Dobado, Truong, Pelaez, Kaiser, Siegel, Weise, Oller, Oset, Meißner, Lutz, FKG, …
    - T-matrix from Bethe-Salpeter equation in a on-shell form (derived from N/D method) — Oller, Oset (1999)



  - Resonances appear as poles of the T-matrix on various Riemann sheets (RSs) of the complex energy plane
    - RSs: defined via $\mathrm{Im}\, p_i$ for each channel
    - Bound state: pole on RS-1
    - Resonances: poles on other (unphysical) RSs





1^{-+} kaonic molecules and partners

- S-wave scattering between NGBs (π, K, η) and 1^+ light mesons (as matter fields)
  - Two 1^+ nontets (A_1: 1^{++}, B_1: 1^{+-}):

$$A_1 = \begin{pmatrix} \frac{a_1^0}{\sqrt{2}} + \frac{f_1^8}{\sqrt{6}} & a_1^+ & K_{1A}^+ \\ a_1^- & -\frac{a_1^0}{\sqrt{2}} + \frac{f_1^8}{\sqrt{6}} & K_{1A}^0 \\ K_{1A}^- & \bar{K}_{1A}^0 & -\frac{2f_1^8}{\sqrt{6}} \end{pmatrix} \qquad B_1 = \begin{pmatrix} \frac{b_1^0}{\sqrt{2}} + \frac{h_1^8}{\sqrt{6}} & b_1^+ & K_{1B}^+ \\ b_1^- & -\frac{b_1^0}{\sqrt{2}} + \frac{h_1^8}{\sqrt{6}} & K_{1B}^0 \\ K_{1B}^- & \bar{K}_{1B}^0 & -\frac{2}{\sqrt{6}}h_1^8 \end{pmatrix}$$

- Mass eigenstates are mixtures of flavor eigenstates:

$$\begin{pmatrix} |f_1(1285)\rangle \\ |f_1(1420)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{3P_1} & \sin\theta_{3P_1} \\ -\sin\theta_{3P_1} & \cos\theta_{3P_1} \end{pmatrix} \begin{pmatrix} |f_1^1\rangle \\ |f_1^8\rangle \end{pmatrix} \qquad \begin{pmatrix} |h_1(1170)\rangle \\ |h_1(1415)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{1P_1} & \sin\theta_{1P_1} \\ -\sin\theta_{1P_1} & \cos\theta_{1P_1} \end{pmatrix} \begin{pmatrix} h_1^1 \\ h_1^8 \end{pmatrix}$$

$$\begin{pmatrix} |K_1(1270)\rangle \\ |K_1(1400)\rangle \end{pmatrix} = \begin{pmatrix} \sin\theta_{K_1} & \cos\theta_{K_1} \\ \cos\theta_{K_1} & -\sin\theta_{K_1} \end{pmatrix} \begin{pmatrix} |K_{1A}\rangle \\ |K_{1B}\rangle \end{pmatrix}$$

Mixing angles	θ_{K_1}	θ_{3P_1}	θ_{1P_1}
Set A	$57°$	$52°$	$-17.5°$
Set B	$34°$	$23.1°$	$28.0°$

Preferred in H.-Y. Cheng, PLB 707, 116 (2012)

1^{-+} kaonic molecules and partners

- Resonances w/ $I=0, J^{PC}=1^{-+}$ (η_1): : pole positions, Riemann sheets, (peak mass, peak width), couplings
  - Poles obtained neglecting (peak mass/width obtained with) axial meson widths

Poles (Set B) [GeV] (peak mass, peak width)	Channels and effective couplings				
$1.39 \pm 0.01 - i(0.04 \pm 0.01)$ $(-+++\,+)$	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
$(1.42, 0.34)$	$5.21 + i3.03$	$0.81 + i0.53$	0.00	$0.55 + i0.54$	0.00
1.70 ± 0.02 $(-+++\,+)$	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
$(1.70, 0.10)$	$0.25 + i0.67$	$8.34 - i0.08$	$1.27 - i0.01$	$0.37 + i0.17$	$2.58 - i0.01$
1.84 ± 0.03 $(---+\,+)$	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
$(1.85, 0.18)$	$0.15 + i0.62$	$0.33 - i0.27$	$1.83 + i0.09$	$9.05 + i0.17$	$3.81 - i0.20$

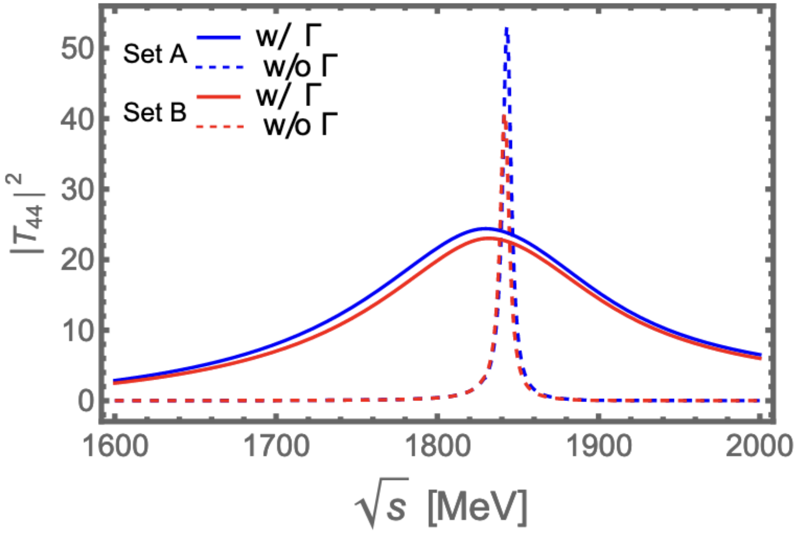
1^{-+} kaonic molecules and partners

- Resonances w/ $I = 0, J^{PC} = 1^{-+}$ (η_1): pole positions, Riemann sheets, (peak mass, peak width), couplings

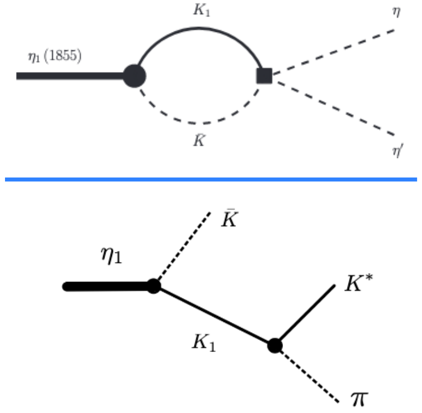
$M_{\eta_1}^{\text{exp}} = 1855 \pm 9^{+6}_{-1}$ MeV
$\Gamma_{\eta_1}^{\text{exp}} = 188 \pm 18^{+3}_{-9}$ MeV

Poles [GeV] (peak mass, peak width)	Channels				
1.84 ± 0.03 $(---++)$	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
$(1.85, 0.18)$	$0.15 + i0.62$	$0.33 - i0.27$	$1.83 + i0.09$	$9.05 + i0.17$	$3.81 - i0.20$

- Resonances get widths from unstable axial-vector mesons:



- This pole [$K_1(1400)\bar{K}$ molecular state] may correspond to $\eta_1(1855)$ X.-K. Dong, Y.-H. Lin, B.-S. Zou, SCPMA 65, 261011 (2022)
- Estimate of the ratio of partial widths:

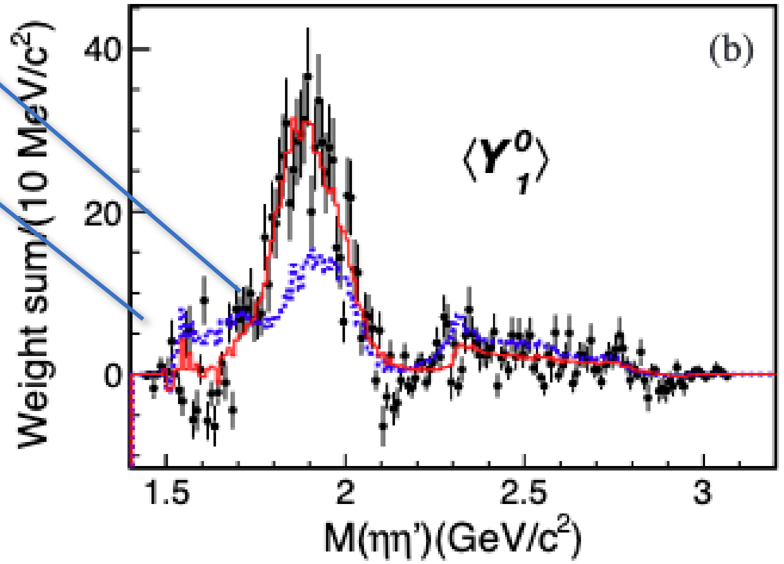


$= \frac{\mathcal{O}(10\text{ MeV})}{\mathcal{O}(80\text{ MeV})}$

1^{-+} kaonic molecules and partners

- Resonances w/ $I = 0, J^{PC} = 1^{-+}$ (η_1): pole positions, Riemann sheets, (peak mass, peak width), couplings

Poles [GeV] (peak mass, peak width)	Channels and effective couplings				
$1.39 \pm 0.01 - i(0.04 \pm 0.01)$ $(-+++\,+)$	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
$(1.42, 0.34)$	$5.21 + i3.03$	$0.81 + i0.53$	0.00	$0.55 + i0.54$	0.00
1.70 ± 0.02 $(-+++\,+)$	$a_1\pi$	$K_1(1270)\bar{K}$	$f_1(1285)\eta$	$K_1(1400)\bar{K}$	$f_1(1420)\eta$
$(1.70, 0.10)$	$0.25 + i0.67$	$8.34 - i0.08$	$1.27 - i0.01$	$0.37 + i0.17$	$2.58 - i0.01$



- Expected dominant decay channels
  - $K_1(1270)\bar{K}: \bar{K}\rho\pi$
  - $K_1(1400)\bar{K}: \bar{K}K^*\pi$

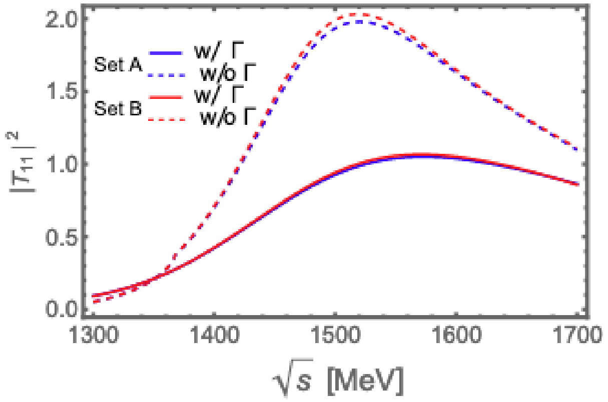
1^{-+} kaonic molecules and partners

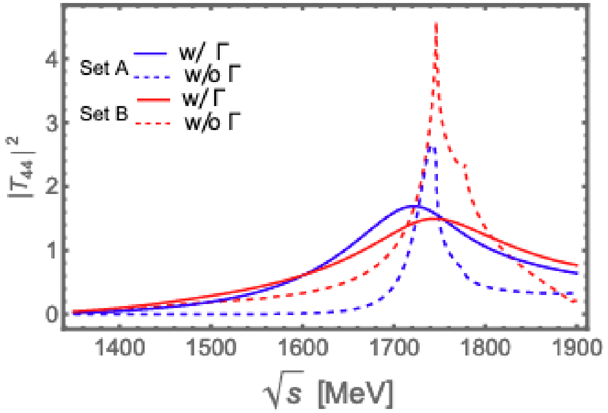
- Resonances w/ $I=1, J^{PC}=1^{-+}$ (π_1): pole positions, Riemann sheets, (peak mass, peak width), couplings
  - Poles obtained neglecting (peak mass/width obtained with) axial meson widths

Poles (Set B) [GeV] (peak mass, peak width)		Channels and effective couplings				
$1.47 \pm 0.01 - i(0.12 \pm 0.02)$ $(--+++\,+)$	$b_1\pi$	$f_1(1285)\pi$	$f_1(1420)\pi$	$K_1(1270)\bar{K}$	$a_1\eta$	$K_1(1400)\bar{K}$
$(\mathbf{1.57, 0.50})$	$5.27 + i4.31$	$0.01 - i0.03$	$0.03 - i0.06$	$1.97 - i1.81$	$0.02 - i0.08$	$0.91 + i1.07$
$1.77 \pm 0.01 - i(0.01 \pm 0.01)$ $(---++\,+)$	$b_1\pi$	$f_1(1285)\pi$	$f_1(1420)\pi$	$K_1(1270)\bar{K}$	$a_1\eta$	$K_1(1400)\bar{K}$
$(\mathbf{1.72, 0.20})$	$0.13 + i1.44$	$1.37 - i0.25$	$2.86 - i0.50$	$4.80 - i2.29$	$3.53 - i0.64$	$4.54 - i1.77$

$\pi_1(1400)$ / $\pi_1(1600)$?

PDG 2024
$\pi_1(1600)$ T-Matrix Pole $\sqrt{s}$
$(1480 - 1680) - i(150 - 300)$ MeV





Two more strange mesons with 1^- and mass around 1.7 GeV

➢ Relation to $K^*(1680)$?

Remarks regarding the axial mesons

- The WT terms for both $K^*\bar{K}$ $(I=0)$ and $K^*\bar{K}$ $(I=1)$ are attractive, expectations:
  - $I=0$: stronger attraction ⇒ bound state (if only single channel)
  - $I=1$: weaker attraction ⇒ virtual state (if only single channel) ⇒ threshold cusp

TABLE III. C_{ij} coefficients in isospin base for $S=0$, $I=0$. The first column indicates the G parity.

G		$\frac{1}{\sqrt{2}}(\bar{K}^*K+K^*\bar{K})$	$\phi\eta$	$\omega\eta$	$\rho\pi$	$\frac{1}{\sqrt{2}}(\bar{K}^*K-K^*\bar{K})$
+	$\frac{1}{\sqrt{2}}(\bar{K}^*K+K^*\bar{K})$	−3	0	0	0	0
−	$\phi\eta$	0	0	0	0	$\sqrt{6}$
−	$\omega\eta$	0	0	0	0	$-\sqrt{3}$
−	$\rho\pi$	0	0	0	−4	$\sqrt{3}$
−	$\frac{1}{\sqrt{2}}(\bar{K}^*K-K^*\bar{K})$	0	$\sqrt{6}$	$-\sqrt{3}$	$\sqrt{3}$	−3

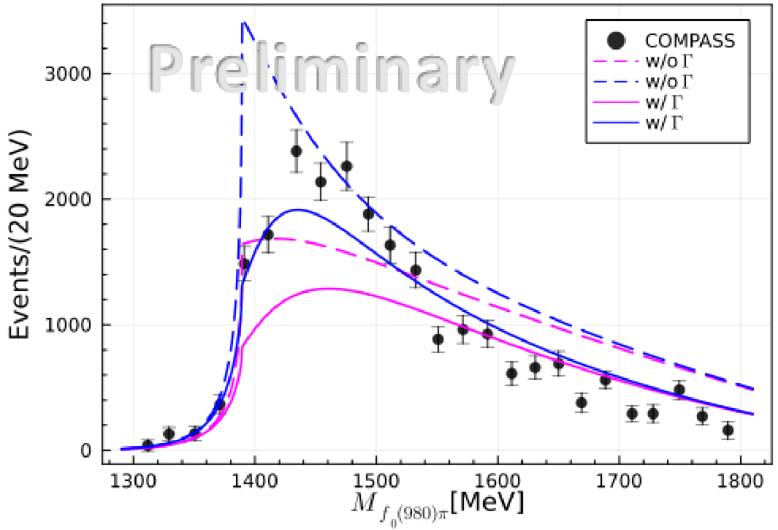
TABLE IV. C_{ij} coefficients in isospin base for $S=0$, $I=1$. The first column indicates the G parity.

G		$\frac{1}{\sqrt{2}}(\bar{K}^*K+K^*\bar{K})$	$\phi\pi$	$\omega\pi$	$\rho\eta$	$\rho\pi$	$\frac{1}{\sqrt{2}}(\bar{K}^*K-K^*\bar{K})$
+	$\frac{1}{\sqrt{2}}(\bar{K}^*K+K^*\bar{K})$	−1	$-\sqrt{2}$	1	$\sqrt{3}$	0	0
+	$\phi\pi$	$-\sqrt{2}$	0	0	0	0	0
+	$\omega\pi$	1	0	0	0	0	0
+	$\rho\eta$	$\sqrt{3}$	0	0	0	0	0
−	$\rho\pi$	0	0	0	0	−2	$\sqrt{2}$
−	$\frac{1}{\sqrt{2}}(\bar{K}^*K-K^*\bar{K})$	0	0	0	0	$\sqrt{2}$	−1

Roca, Oset, Singh, PRD 72, 014002 (2005) [virtual state poles overlooked]

➢ Comparison of the $I=1$ $K^*\bar{K}$ virtual state lineshape with COMPASS data for $a_1(1420)$

M.-J. Yan et al., in preparation



Summary

- Plenty of molecular states are expected from S-wave kaonic interaction with other hadrons
  - For hadron H being $I = 1/2$ in SU(3) octet, isoscalar HK is 3 times more attractive than isovector pair
    - Bound states for isoscalar, virtual state for isovector
  - $\eta_1(1855)$ could be $K_1(1400)\bar{K}$ molecular state, whose partners need to be searched for
  - $a_1(1420)$ could exist as a $K^*\bar{K}$ virtual state, analyzing data with S-wave $\pi\pi$ outside the $f_0(980)$ mass region to distinguish it from triangle singularity effects

Thank you for your attention!