Study of some (non-)conventional mesons in the framework of effective models.

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Excited QCD 2020

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Publications

- F. Giacosa, M. Piotrowska and S. Coito, "$X(3872)$ as virtual companion pole of the charm-anticharm state $\chi_{c1}(2P)$," Int. J. Mod. Phys. A **34** (2019) no.29, 1950173.
- M. Piotrowska, F. Giacosa and P. Kovacs, "Can the $\psi(4040)$ explain the peak associated with $Y(4008)$?," Eur. Phys. J. C **79** (2019) no.2, 98.
- T. Wolkanowski, M. Sołtysiak and F. Giacosa, "$K_0^*(800)$ as a companion pole of $K_0^*(1430)$," Nucl. Phys. B **909** (2016) 418.

Outline

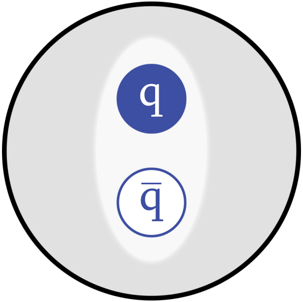
Motivation

- Understanding of the hadronic resonances
- Study the nature of CONVENTIONAL and NON-CONVENTIONAL states:
  - scalar kaonic sector: $K_0^*(1430)$ and $K_0^*(700)$
  - vector sector: $\psi(4040)$ and $Y(4008)$
  - axial-vector resonances: $\chi_{c1}(2P)$ and $X(3872)$

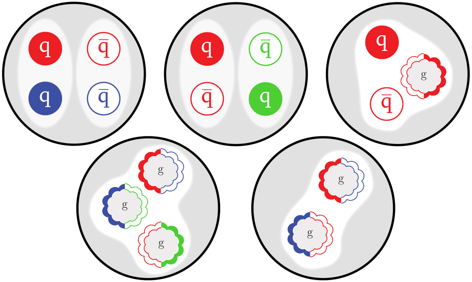
Definition(s)

- A meson is a strongly interacting particle with integer spin.
- A meson is a strongly interacting particle with zero baryon number.

CONVENTIONAL



NON-CONVENTIONAL



$K_0^*(1430)$ and $K_0^*(700)$ in PDG

$K_0^*(1430)$ [nn] $I(J^P) = \frac{1}{2}(0^+)$

Mass $m = 1425 \pm 50$ MeV
Full width $\Gamma = 270 \pm 80$ MeV

$K_0^*(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(93 ± 10) %	619
$K\eta$	$(8.6^{+2.7}_{-3.4})$ %	486

$K_0^*(700)$ $I(J^P) = \frac{1}{2}(0^+)$

also known as κ; was $K_0^*(800)$

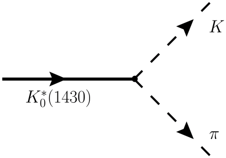
Needs confirmation. See the mini-review on scalar mesons under $f_0(500)$ (see the index for the page number).

$K_0^*(700)$ T-Matrix Pole $\sqrt{s}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
(630–730) − i (260–340) OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$(670 \pm 18) - i\,(295 \pm 28)$	[1] PELAEZ	17	RVUE	
$(764 \pm 63^{+71}_{-54}) - i\,(306 \pm 149^{+143}_{-85})$	[2] ABLIKIM	11B	BES2	1.3k $J/\psi \to K_S^0 K_S^0 \pi^+\pi^-$
$(665 \pm 9) - i\,(268^{+21}_{-6})$	[3] GUO	11B	RVUE	
$(849 \pm 77^{+18}_{-14}) - i\,(256 \pm 40^{+46}_{-22})$	[2] ABLIKIM	10E	BES2	1.4k $J/\psi \to K^\pm K_S^0 \pi^\mp \pi^0$
$(663 \pm 8 \pm 34) - i\,(329 \pm 5 \pm 22)$	[4] BUGG	10	RVUE	S-matrix pole
$(706.0 \pm 1.8 \pm 22.8) - i\,(319.4 \pm 2.2 \pm 20.2)$	[5] BONVICINI	08A	CLEO	141k $D^+ \to K^-\pi^+\pi^+$
$(841 \pm 30^{+81}_{-73}) - i\,(309 \pm 45^{+48}_{-72})$	[2] ABLIKIM	06C	BES2	25k $J/\psi \to \overline{K}^*(892)^0 K^+\pi^-$
$(750^{+30}_{-55}) - i\,(342 \pm 60)$	[6] BUGG	06	RVUE	
$(658 \pm 13) - i\,(279 \pm 12)$	[7] DESCOTES-G..	06	RVUE	$\pi K \to \pi K$
$(757 \pm 33) - i\,(279 \pm 41)$	[8] GUO	06	RVUE	

The model

THE LAGRANGIAN: $\mathcal{L}_{int} = aK_0^{*+}K^-\pi^0 + bK_0^{*+}\partial_\mu K^-\partial^\mu\pi^0 + \ldots$



DECAY WIDTH: $\Gamma_{K_0^*}(m) = 3\frac{|\vec{k}_1|}{8\pi m^2}\left[a - b\frac{m^2-m_K^2-m_\pi^2}{2}\right]^2 F_\Lambda(m)$

$$\left|\vec{k}_1\right| = \frac{\sqrt{m^4+\left(m_\pi^2-m_K^2\right)^2-2\left(m_\pi^2+m_K^2\right)m^2}}{2m} \times \theta(m - m_\pi - m_K)$$

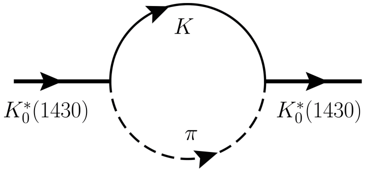
FORM FACTOR: $F_\Lambda(m) = e^{-2k^2(m)/\Lambda^2}$

The model

THE PROPAGATOR: $\Delta_{K_0^*}(p^2 = m^2) = \frac{1}{m^2 - M_0^2 + \Pi(m^2) + i\varepsilon}$

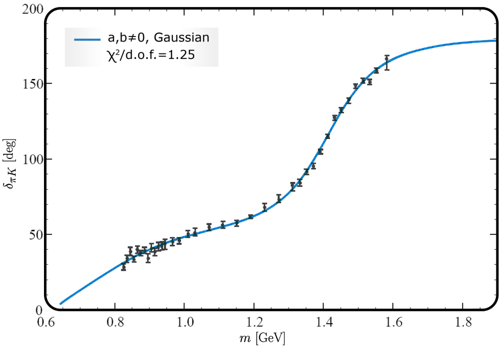
SPECTRAL FUNCTION: $d_{K_0^*}(m) = \frac{2m}{\pi} |Im\Delta_{K_0^*}(p^2 = m^2)|$

normalization condition: $\int\limits_0^\infty d_{K_0^*}(m)dm = 1$



Phase-shift

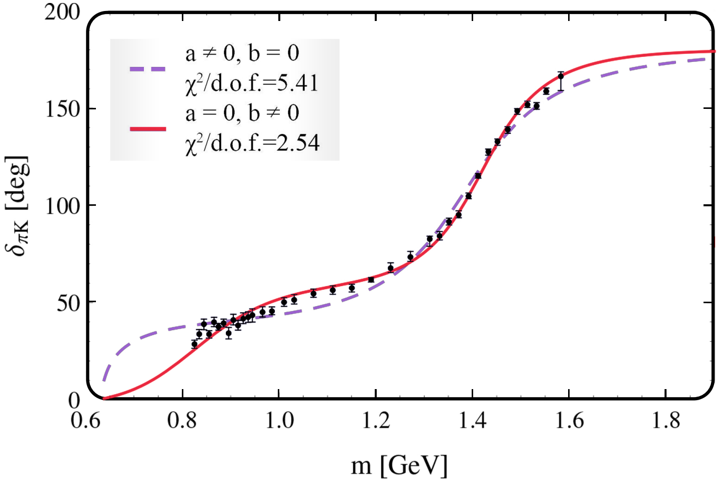
$$\delta(m) = \frac{1}{2}\arccos\left[1 - \pi\Gamma_{K_0^*}(m) d_{K_0^*}(m)\right] \ .$$



Fit

a	$1.60\pm\ 0.22\ GeV$
b	$-11.16\pm0.82\ GeV^{-1}$
Λ	$0.496\pm0.008\ GeV$
M_0	$1.204\pm0.008\ GeV$

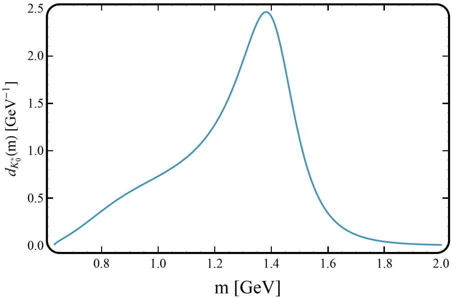
$\chi^2/d.o.f. = 1.25$



only nonderivative
$\mathcal{L}_{int} = aK_0^{*+}K^-\pi^0 + \ldots$
$\chi^2/d.o.f. = 5.41$

only derivative
$\mathcal{L}_{int} = bK_0^{*+}\partial_\mu K^-\partial^\mu\pi^0 + \ldots$
$\chi^2/d.o.f. = 2.54$

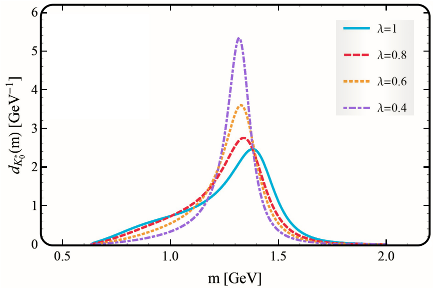
Spectral function and poles position



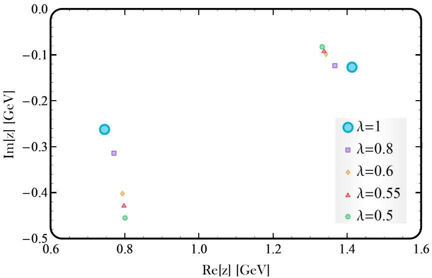
$$K_0^*(1430) : (1.413 \pm 0.057) - (0.127 \pm 0.011)\mathrm{i}\ (GeV)$$
$$K_0^*(700) : (0.745 \pm 0.029) - (0.263 \pm 0.027)\mathrm{i}\ (GeV)$$

Large$-N_c$ study

spectral functions



pole position



Scalar resonance $K_0^*(1430)-$ behavior typical for quark-antiquark state.

Scalar resonance $K_0^*(700)-$ dynamically generated companion pole.

Y(4008)- experimental and theoretical aspects

The Belle Collaboration observed a significant enhancement with mass $M = 4008 \pm 40^{+114}_{-28}$ MeV and width $\Gamma = 226 \pm 44 \pm 87$ MeV when measuring the $e^+e^- \to \pi^+\pi^- J/\Psi$ cross section via ISR.

INTERPRETATIONS OF THE $Y(4008)$ STATE

- **$\psi(3S)$ charmonium state**
  B. Q. Li and K. T. Chao, Phys. Rev. D **79** (2009) 094004
- **$D^*\bar{D}^*$ molecular state**
  W. Xie, L. Q. Mo, P. Wang and S. R. Cotanch, Phys. Lett. B **725** (2013) 148
- **Tetraquark state**
  P. Zhou, C. R. Deng and J. L. Ping, Chin. Phys. Lett. **32** (2015) no.10, 101201.
- **Interference with background**
  D. Y. Chen, X. Liu, X. Q. Li and H. W. Ke, Phys. Rev. D **93** (2016) 014011

What is our idea?

$\psi(4040)$

$\psi(4040)$ $I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4040)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
4039 ± 1 OUR ESTIMATE				
4039.6± 4.3	[1] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4034 ± 6	[2] MO	10	RVUE	$e^+e^- \to$ hadrons
4037 ± 2	[3] SETH	05A	RVUE	$e^+e^- \to$ hadrons
4040 ± 1	[4] SETH	05A	RVUE	$e^+e^- \to$ hadrons
4040 ±10	BRANDELIK	78C	DASP	e^+e^-

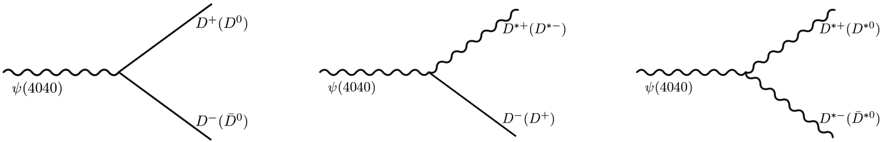
$\psi(4040)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
80 ±10 OUR ESTIMATE				
84.5±12.3	[5] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
87 ±11	[6] MO	10	RVUE	$e^+e^- \to$ hadrons
85 ±10	[7] SETH	05A	RVUE	$e^+e^- \to$ hadrons
89 ± 6	[8] SETH	05A	RVUE	$e^+e^- \to$ hadrons
52 ±10	BRANDELIK	78C	DASP	e^+e^-

Decay channels of the resonance $\psi(4040)$

$V \to PP$ $V \to PV$ $V \to VV$

FEYNMAN DIAGRAMS



DECAY CHANNELS

$\psi(4040) \to D^+D^-$
$\psi(4040) \to D^0\bar{D}^0$
$\psi(4040) \to D_s^+D_s^-$

$\psi(4040) \to D^{*0}\bar{D}^0 + h.c.$
$\psi(4040) \to D^{*+}D^- + h.c.$
$\psi(4040) \to D_s^{*+}D_s^- + h.c.$

$\psi(4040) \to D^{*0}\bar{D}^{*0}$
$\psi(4040) \to D^{*+}D^{*-}$

Lagrangian and decay width

THE LAGRANGIAN | DECAY WIDTH

$$V \to PP$$

$$\mathcal{L}_{\psi DD} = i g_{\psi DD} \psi_\mu \left[\left(\partial^\mu D^+ \right) D^- \right] + h.c \qquad \Gamma = \frac{|\vec{k}|^3}{6\pi m_\psi^2} g_{\psi DD}^2 F_\Lambda$$

$$V \to PV$$

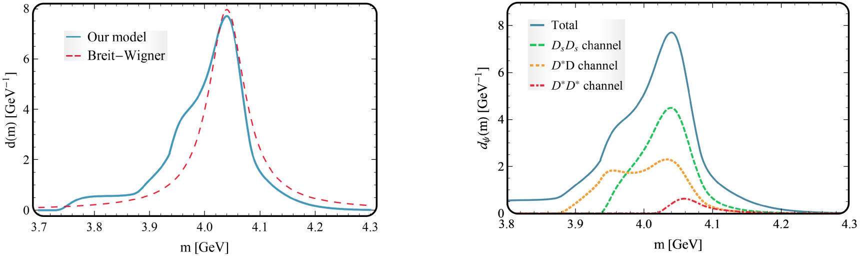
$$\mathcal{L}_{\psi D^* D} = i g_{\psi D^* D} \tilde{\psi}_{\mu\nu} \left[D^\mu D^{*+\nu} D^- \right] + h.c \qquad \Gamma = \frac{2}{3} \frac{|\vec{k}|^3}{\pi} g_{\psi D^* D}^2 F_\Lambda$$

$$V \to VV$$

$$\mathcal{L}_{\psi D^* D^*} = i g_{\psi D^* D^*} \left[\psi_{\mu\nu} \left(D^{*+\mu} D^{*-\nu} \right) \right] + h.c \qquad \Gamma = \frac{2}{3} \frac{|\vec{k}|^3}{\pi m_{D_c^*}^2} g_{\psi D^* D^*}^2 \left[2 + \frac{|\vec{k}|^2}{m_{D_c^*}^2} \right] F_\Lambda$$

Results

SPECTRAL FUNCTION



POLES POSITION

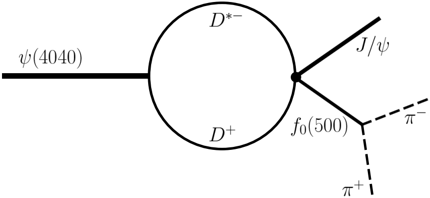
$\psi(4040)$: $(4.053 \pm 0.04) - (0.040 \pm 0.010)i$ GeV

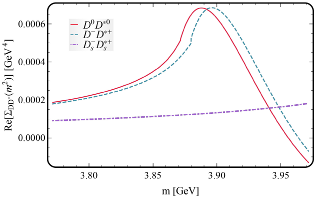
Second pole: $(3.934 \pm 0.006) - (0.030 \pm 0.001)i$ GeV

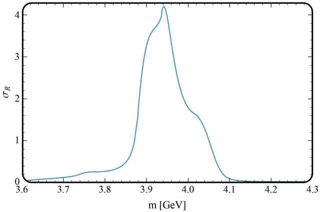
THIS IS NO Y(4008)!

Dacay into $J/\psi\pi^+\pi^-$

$\psi(4040) \to DD^* \to J/\psi + f_0(500) \to J/\psi + \pi^+ + \pi^-$.



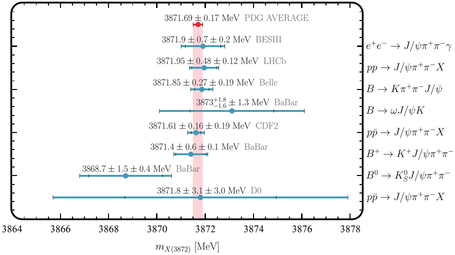




The strong coupling of $\psi(4040)$ to D^*D generates the broad enhancement: $Y(4008)$ is not a real resonance.

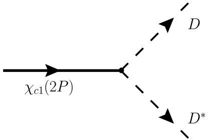
$X(3872)$- experimental and theoretical aspects

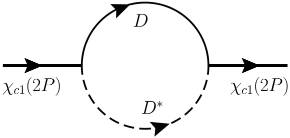
- axial-vector resonance with quantum numbers $J^{PC} = 1^{++}$.
- Reported in the PDG under the name $\chi_{c1}(3872)$.
- For the first time observed in 2003 by the Belle Collaboration as the first state from the family of X, Y and Z states.
- The PDG mass of $X(3872)$ is $m = 3871.69 \pm 0.17$ MeV, while the decay width is $\Gamma < 1.2$ MeV (90% CL).
- Theoretical assignments: $D^0 D^{*0}$ molecular state, diquark-antidiquark state and more...



The model

THE LAGRANGIAN: $\mathcal{L}_{\chi_{c1}(2P)DD^*} = g_{\chi_{c1}DD^*}\chi_{c1,\mu}\left[D^{*0,\mu}\bar{D}^0 + D^{*+,\mu}D^- + h.c.\right]$.





$\Gamma_{\chi_{c1}(2P)\to D^{*0}\bar{D}^0+h.c.}(m)$
$\Gamma_{\chi_{c1}(2P)\to D^{*+}D^-+h.c.}(m)$

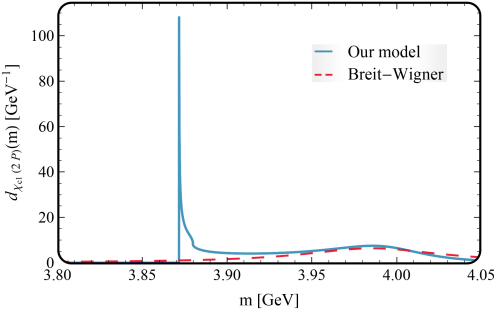
$\Pi(m^2)$

THE PROPAGATOR: $\Delta(s) = \frac{1}{s-m_0^2+\Pi(s)}$.

SPECTRAL FUNCTION: $d_{\chi_{c1}(2P)}(m) = -\frac{2m}{\pi}\,\text{Im}[\Delta(s=m^2)]$.
normalization condition: $\int_{m_{D^{*0}}+m_{D^0}}^{\infty} \text{dm}\; d_{\chi_{c1}(2P)}(m) = 1$.

Results

SPECTRAL FUNCTION



POLES POSITION

$\chi_{c1}(2P)$: $3.995 - 0.036i$ GeV (III RS)

$X(3872)$: $3.87164 - i\varepsilon$ GeV (II RS)

$X(3872)$ is a vitual companion pole of conventional $c\bar{c}$ state $\chi_{c1}(2P)$.

Conclusions

- Scalar kaons: out of one seed state → 2 poles appears
  - $K_0^*(1430)$ corresponds to a peak in the spectral function (predominantly quark-antiquark state)
  -$K_0^*(700)$: "no peak" but there is a pole (state generated dynamically).
- Vector charmonium states: out of one seed state → 2 poles appears
  - $\psi(4040)$ corresponds to a peak in the spectral function (predominantly charm-anticharm state)
  - $Y(4008)$: is not a genuine resonance, but a peak generated by the $\psi(4040)$ and DD^* loops with $J/\psi\pi^+\pi^-$ in the final state.
- Axial-vector charmonium states: out of one seed state → 2 poles appears
  -$\chi_{c1}(2P)$: related to the broad peak in the spectral function (predominantly charm-anticharm state)
  -$X(3872)$: related to the narrow peak in the spectral function (virtual companion pole of the $\chi_{c1}(2P)$ state.)

THANK YOU FOR YOUR ATTENTION