HOW MANY VECTOR STATES SIT IN THE ENERGY RANGE FROM 4.2 TO 4.35 GEV?

February 28, 2024 | Leon von Detten | IAS-4/IKP-3 QWG 2024

based on arXiv:2402.03057 in collaboration with Christoph Hanhart, Vadim Baru, Qian Wang, Daniel Winney and Qiang Zhao

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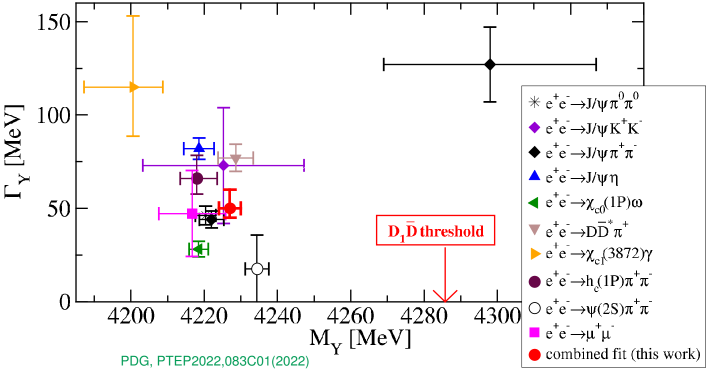
Motivation



PDG, PTEP2022,083C01(2022)

- Why do mass and decay width scatter so much for different reactions?
- How big is the influence of the $D_1\bar{D}$ threshold?
- Why $Y(4320)$ only seen in $e^+e^- \to J/\psi\pi\pi$?

Simultaneous fit of almost all final states.

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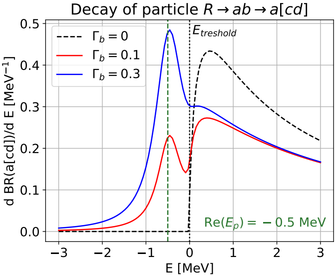
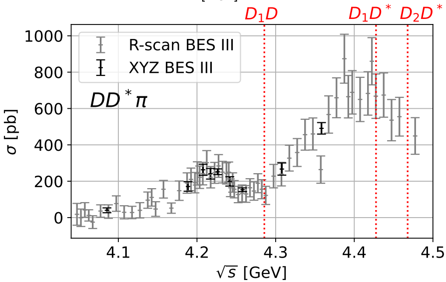
Hadronic Molecules

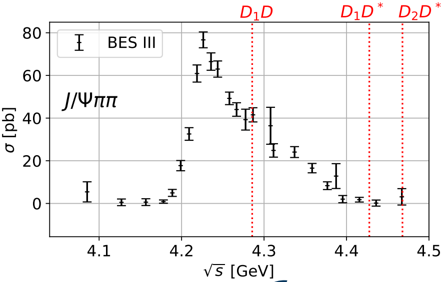


- Coupling to 2 hadron continuum maximal
  $\to$ Loop contributions at leading order
  $\to$ Possible imprint of threshold on lineshape

Braaten and Lu PRD76(2007)094028, Hanhart et al.,PRD81(2010)094028

- $Y(4230) \to D_1\bar{D} \to [D^*\pi]\bar{D}$ main decay channel
- Also $D_1\bar{D}^*$ and $D_2\bar{D}^*$ 1^{--} bound states in molecular scenario





BES III,PRD106(2022)7,072001 BES III, PRL130(2023)12,1219011

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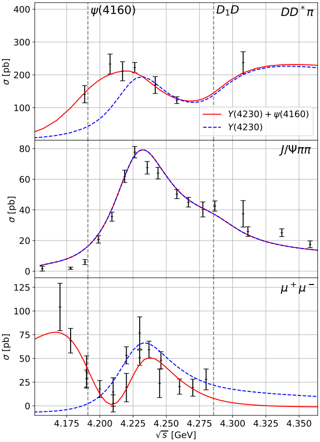
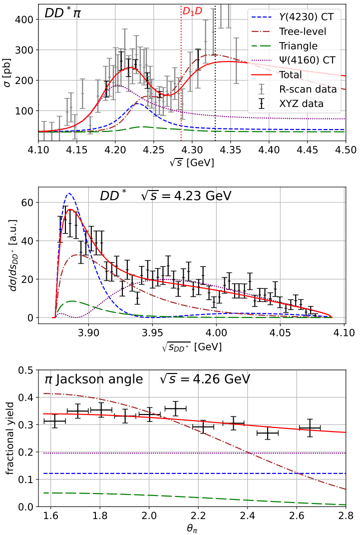
$\psi(4160)$

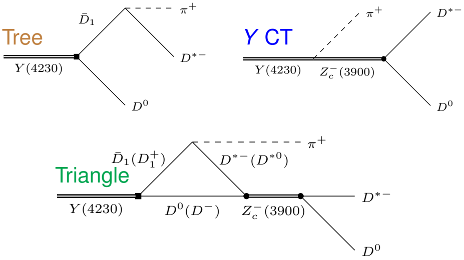


BES III, PRD102(2020)112009

- Narrow structure in $J/\psi\pi\pi$ incompatible with broad structure in $D\bar{D}^*\pi$
- $\mu^+\mu^-$ channel shows destructive interference
- Values from RPP
  $m_{\Psi(4160)} = (4191\pm5)$ MeV
  $\Gamma_{\Psi(4160)} = (70\pm10)$ MeV
- experimental $Y(4230)$ extraction:
  $D^0 D^{*-}\pi^+$: $\Gamma_Y = (77\pm6.3\pm6.8)$ MeV
  $J/\psi\pi^+\pi^-$: $\Gamma_Y = (41.8\pm2.9\pm2.7)$ MeV
  $\mu^+\mu^-$: $\Gamma_Y = (47.2\pm22.8\pm10.5)$ MeV

$D^0 D^{*-}\pi^+$

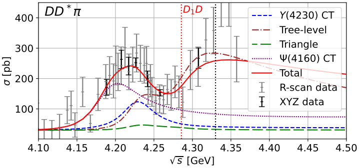


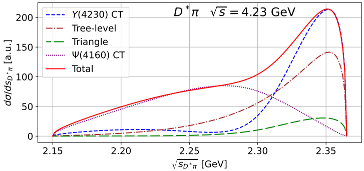


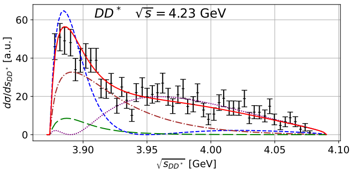
- Strong enhancement at $D_1\bar{D}$ threshold, mainly driven by D_1 D-wave decay
- $D_1 \to D^*\pi$ decay in $S-$ and $D-$wave
- Phase of contact terms fixed by $D^*\bar{D}$, $J/\psi\pi$ rescattering into Z_c

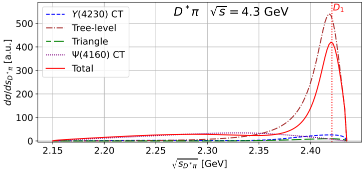
BES III, PRD92(2015)9,092006; PRL112(2014)2,022001

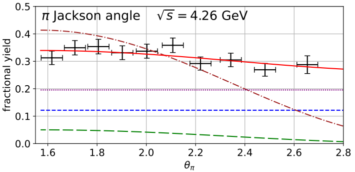
$D^0 D^{*-} \pi^+$







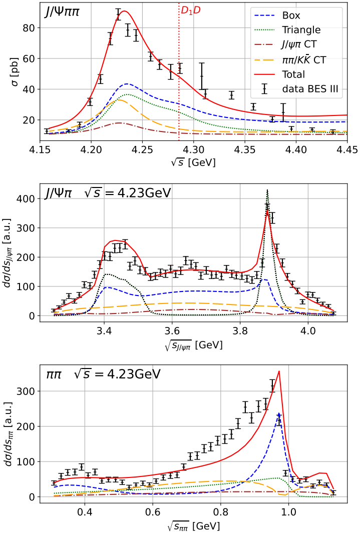


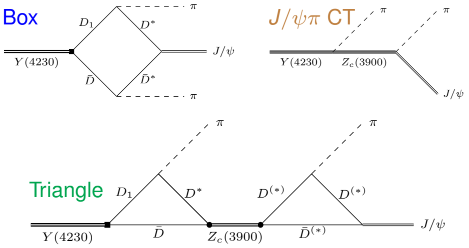


- Molecular scenario predicts strong D_1 signal in $D^*\pi$ invariant mass distribution

BES III, PRD92(2015)9,092006; PRL112(2014)2,022001

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





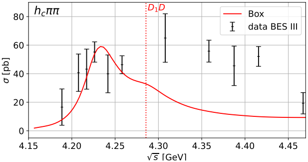
+ different box and triangle topologies

- Asymmetry in total crosssection generated by $D_1\bar{D}$ intermediate state
- $\pi\pi/KK$ s-wave final state interaction approx-imate via coupled channel Omnés

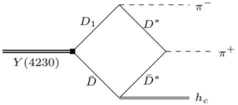
Full FSI: Chen at al., PRD99(2019)7,074016
Danilkin et al., PRD 102(2020)1,016019

BES III, PRL119(2017)7,072001

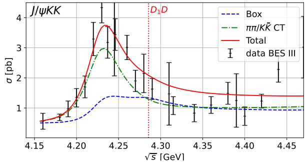
$h_c\pi^+\pi^-$ and $J/\psi K^+K^-$



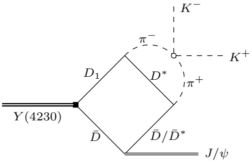
BES III, PRD106(2022)7,072001

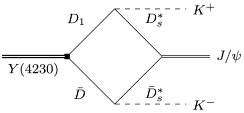


- No contact term due to HQSS
- Triangle requires $D_1\bar{D}^*$ coupling



BES III, CPC46(2022)111002





Full coupled channel analysis will include complete $\{D, D^*\} \otimes \{D_1, D_2\}$ multiplets with SU(3) flavor

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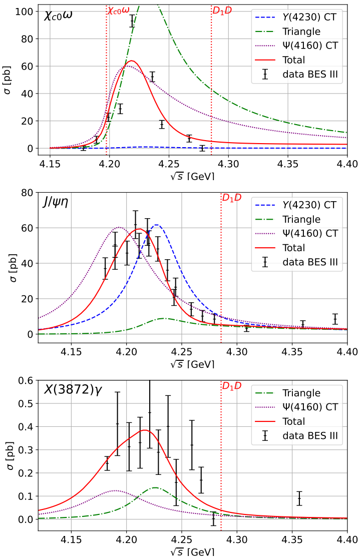
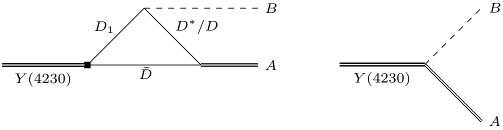
$\chi_{c0}\,\omega$, $J/\psi\,\eta$ and $X(3872)\gamma$



$Y(4230) \to AB$ two body decay



- Main contribution of $Y(4230)$ from triangle loop
- Destructive interference needed to create narrow structure in $\chi_{c0}\omega$
- $Y \to X(3872)\gamma$ contact term subleading

exp. data
BES III,PRD99(2019)9,091103
BES III,PRD102(2020)3,031101
BES III,PRL122(2019)23,232002

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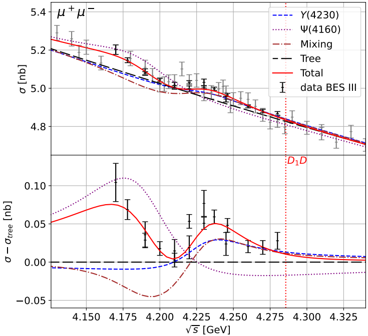
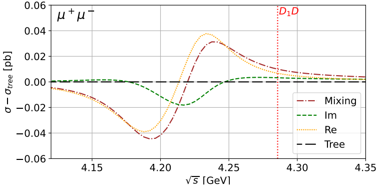
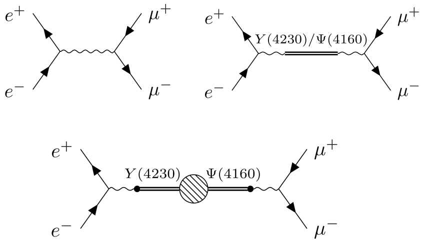
$\mu^+\mu^-$



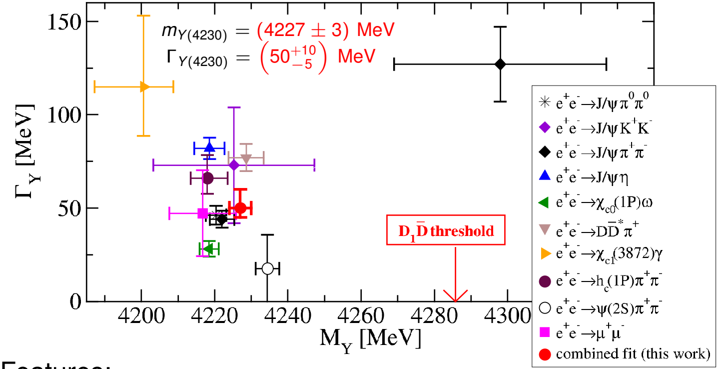
BES III, PRD102(2020)112009





- Sensitive to one free real parameter and one phase
- Imaginary part of Mixing amplitude fixed by optical theorem
- Reproduce destructive interference between $Y(4230)$ and $\Psi(4160)$ observed in data

Conclusion



Key Features:

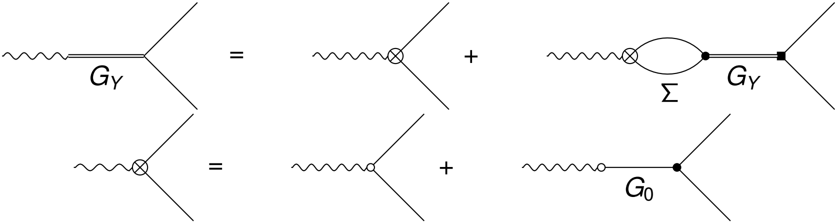
Y(4230) as $D_1\bar{D}$ molecule and inclusion of $\psi(4160)$

Outlook:

Coupled channel analysis with complete $\{D, D^*\} \otimes \{D_1, D_2\}$ multiplets

Appendix

Y4230



$$G_Y = G_0 + G_0 g_{Y0}(2\omega_Y \Sigma_{D_1 D}) g_{Y0} G_Y \,.$$

$J^{PC} = 1^{--}$ isosinglet wavefunction

$$|Y(4230)(\mathcal{C}=-1, I=0)\rangle = -\frac{1}{2}\left(|D_1^+ D^-\rangle + |D^+ D_1^-\rangle + |D_1^0 \bar{D}^0\rangle + |D^0 \bar{D}_1^0\rangle\right)$$

Lagrangian constructed by imposing invariance under heavy-quark spin and chiral symmetry

Lagrangian

Define superfiels for light-quark spin doublets:

$$H_a^{(Q)} = \frac{1+v}{2}\left[D_a^{*\mu}\gamma_\mu - D_a\gamma_5\right]$$

$$T_a^{(Q)^\mu} = \frac{1+v}{2}\left[D_{2a}^{\mu\nu}\gamma_\nu - \sqrt{\tfrac{3}{2}}D_{1a\nu}\gamma_5(g^{\mu\nu} - \tfrac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu))\right]$$

Relevant terms for the interaction

$$\begin{aligned}\mathcal{L}_{\text{int}} = {} & g\langle H_b^{(Q)}\mathcal{A}_{ba}\gamma_5\bar{H}_a^{(Q)}\rangle + k\langle T_b^{(Q)\mu}\mathcal{A}_{ba}\bar{T}_b^{(Q)}\rangle \\ & + \frac{h_1}{\Lambda_\chi}\langle T_b^{(Q)\mu}(D_\mu\mathcal{A})_{ba}\gamma_5\bar{H}_a^{(Q)}\rangle + \frac{h_2}{\Lambda_\chi}\langle T_b^{(Q)\mu}(D\mathcal{A}_\mu)_{ba}\gamma_5\bar{H}_a^{(Q)}\rangle \\ & + g\langle \bar{H}_a^{(\bar{Q})}\mathcal{A}_{ab}\gamma_5 H_b^{(\bar{Q})}\rangle + k\langle \bar{T}_a^{(\bar{Q})\mu}\mathcal{A}_{ab}T_b^{(\bar{Q})}\rangle \\ & + \frac{h_1}{\Lambda_\chi}\langle \bar{T}_a^{(\bar{Q})\mu}(\mathcal{A}\overleftarrow{D}_\mu)_{ab}\gamma_5 H_b^{(\bar{Q})}\rangle + \frac{h_2}{\Lambda_\chi}\langle \bar{T}_a^{(\bar{Q})\mu}(\mathcal{A}_\mu\overleftarrow{D})_{ab}\gamma_5 H_b^{(\bar{Q})}\rangle + \text{h.c.}\end{aligned}$$

Parameters

	Name		Value
Y	m_Y		(4227 ± 0.4) MeV
	g_{Y0}	–	(10.4 ± 0.2) GeV
	Γ_{in}^{Y}		(54 ± 1) MeV
	$1/f_Y$	–	(0.012 ± 0.001)
	$\delta_{Y\gamma}$		$(17.1 \pm 0.1)^o$
ψ	$1/f_\psi$	–	(0.023 ± 0.003)
	$\delta_{\psi\gamma}$		$(67 \pm 2)^o$
Z_c	m_Z		(3884 ± 1) MeV
	g_{Z0}		(4.15 ± 0.06) GeV
	Γ_{in}^{Z}		(48 ± 1) MeV
$D\bar{D}^*\pi$	$\alpha_1^{(1)}$	–	(128 ± 12)
	$\alpha_2^{(1)}$	–	(3.95 ± 0.01) GeV
	$\beta_1^{(1)}$	–	(202 ± 18)
	$\beta_2^{(1)}$	–	(3.89 ± 0.1) GeV

* $\psi(4160)$ mass $m_\psi = 4191$ MeV and width $\Gamma_\psi = 70$ MeV fixed from RPP

	Name		Value
$J/\psi\pi^+\pi^-$	$\alpha_1^{(2)}$	–	(133.9 ± 4)
	g_1	–	$(14.9 \pm 0.9)\, 10^{-3}$
	g_8		$(24 \pm 1)\, 10^{-3}$
	h_1	–	$(16.8 \pm 2.4)\, 10^{-3}$
	h_8		$(15 \pm 0.7)\, 10^{-3}$
	$\beta_1^{(2)}$		(0 ± 0.1)
	$c_{\text{CT}}^{\triangle}$	–	(0.381 ± 0.1) GeV^2
	$f_{J/\psi}$		456 MeV
$\chi_{c0}\omega$	$c_{\chi_{c0}\omega}^{\triangle}$		(1.469 ± 0.015) GeV^2
	$c_{\chi_{c0}\omega}^{Y}$		$(0.36 \pm 0.07)\, 10^{-3}$
	$c_{\chi_{c0}\omega}^{\psi}$	–	$(16 \pm 0.5)\, 10^{-3}$
$J/\psi\eta$	$c_{J/\psi\eta}^{Y}$		$(67.3 \pm 3.4)\, 10^{-3}$ GeV^{-1}
	$c_{J/\psi\eta}^{\psi}$		$(298 \pm 11)\, 10^{-3}$ GeV^{-1}
$X\gamma$	$c_{X\gamma}^{Y}$		(0.71 ± 0.15) GeV^2
	$c_{X\gamma}^{\psi}$		(0.017 ± 0.003) GeV
$\mu^+\mu^-$	c_{mix}		(0.6 ± 0.01)

$\pi\pi - K\bar{K}$ final state interaction

$$\text{disc}\mathcal{M}_j^I(s) = 2i\sum_k T_{jk}^*(s)\sigma_k(s)\mathcal{M}_k^I(s)$$

Solution given by Muskhelishvili Omn'es function

Full amplitude expressed by:

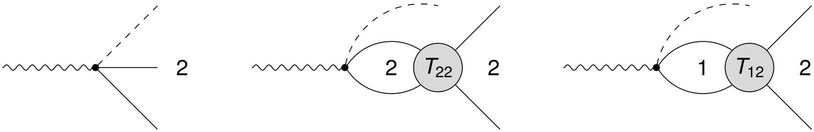
$$\mathcal{M}_j^{\text{full}}(s) = \mathcal{M}_j + \Gamma_j = \mathcal{M}_j + \sum_k \Omega_{jk}\left[(\mathcal{P}_{n-1})_k + \sum_{lm}\frac{s^n}{\pi}\int\frac{z}{z^n}\frac{\Omega_{kl}^{-1}(z)T_{lm}(z)\sigma_m(s)\mathcal{M}_m^0(z)}{z-s}\right]$$
$$= \left[\mathcal{M}_j^{l>0} + \mathcal{M}_j^0\right] + \sum_k\left[\Omega_{jk}\left((\mathcal{P}_{n-1})_k + \frac{s^n}{\pi}\,\text{P.V.}\int[\ldots]\right) + iT_{jk}\sigma_k\mathcal{M}_k^0\right]$$

Modified S-wave approximately given by

$$(\mathcal{M}_j^0)_{\text{mod}} = \mathcal{M}_j^0 + \sum_k \Omega_{jk}\left(\mathcal{P}_{n-1}\right)_k + \left(iT_{jk}\sigma_k + \frac{1}{\pi}\ln\left(\frac{1}{s/s_{\text{th}}-1}\right)T_{jk}\sigma_k\right)\mathcal{M}_k^0$$

$$(\mathcal{M}_j)_{\text{mod}} = \mathcal{M}_j^{l>0} + (\mathcal{M}_j^0)_{\text{mod}}$$

Production with coupled channel FSI



$$\vec{F} = G_Z \begin{pmatrix} g_1 \left[(E - m_0)\hat{M}_1 + g_2^2 \Sigma_2 (\hat{M}_1 - \hat{M}_2) \right] \\ g_2 \left[(E - m_0)\hat{M}_2 + g_1^2 \Sigma_1 (\hat{M}_2 - \hat{M}_1) \right] \end{pmatrix}$$

$$\longrightarrow \vec{F} = G_Z \begin{pmatrix} g_1 \alpha_1^{(1)} (\alpha_2^{(1)} + E) \\ g_2 \alpha_1^{(2)} (\alpha_2^{(2)} + E) \end{pmatrix}$$