How many vector charmonium(-like) states from 4.2 to 4.35 GeV?

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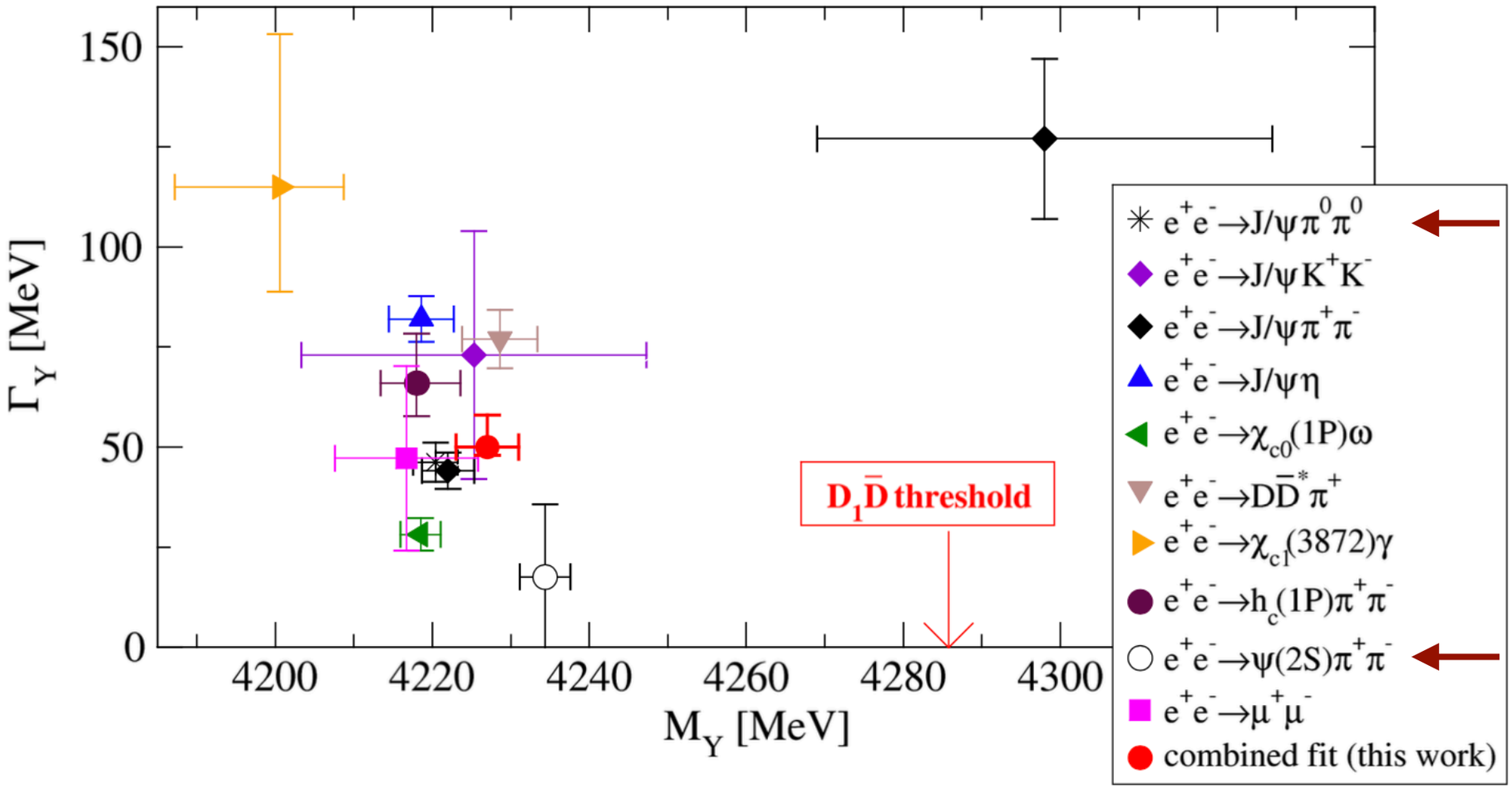
19th-24th Aug. 2024

Detten, Baru, Hanhart, QW, Winney, Zhao, PRD109(2024)116002

Vector charmonium(-like) states

Numerous states between 4.2 GeV and 4.35 GeV

Detten et al., PRD109(2024)116002



- BW resonance parameters in ten channels are not consistent
- An S-wave threshold $D_1\bar{D}$ locates within this energy region
- Large statistic data from BESIII → a global fitting?

Talk by Chen-Ping Shen on 19th (Mon)

The status of vector charmonium(-like) states

The status of vector charmonium-like states

- Hybrid

Spectrum — Close et al., PLB628(2005)215, Kou et al., PLB628(2005)164,

Kalashnikova et al., PRD77(2008)054025, Berwein, et al., PRD92(2015)114019

Decay to spin singlet and disfavor hybrid — Brambilla et al., PRD107(2023)054034

- Hadrocharmonium — Talk by Abhishek Mohapatra on 19th (Mon)

Proposed to explain the $J/\psi\pi\pi$ lineshape — Dubynskiy et al., PLB666(2008)344

The mixing between $(c\bar{c})_1$ and $(c\bar{c})_0$ — Li et al., MPLA29(2014)1450060

The existence of HQSS partners — Cleven et al., PRD92(2015)014005

The status of vector charmonium(-like) states

The status of vector charmonium-like states

- Compact tetraquark

Four states in the mass range 4.22-4.66 GeV Bhavsar et al., NPA1000(2020)121856

Two states to explain the lineshape Ali et al., EPJC78(2018)29

- The $D_1\bar{D}+c.c.$ hadronic molecule Close et al., PRD81(2010)074033

$Y(4230)$ as a $D_1\bar{D}+c.c.$ HM Ding, PRD79(2009)014001, Wang et al., PRL111(2013)132003

Describe the $D\bar{D}^*\pi$ lineshape Chen et al., PRD93(2016)014011, Qin et al., PRD94(2016)054035

Three poles $\psi(4160)$, $Y(4230)$, $Y(4320)$ Nakamura et al., 2312.17658

Poles in HQSS Peng et al., PRD107(2023)016001, Ji et al., PRD129(2022)102002

Two-channel analysis $\psi(4160)$, $Y(4230)$ Chen et al., EPJC78(2018)136

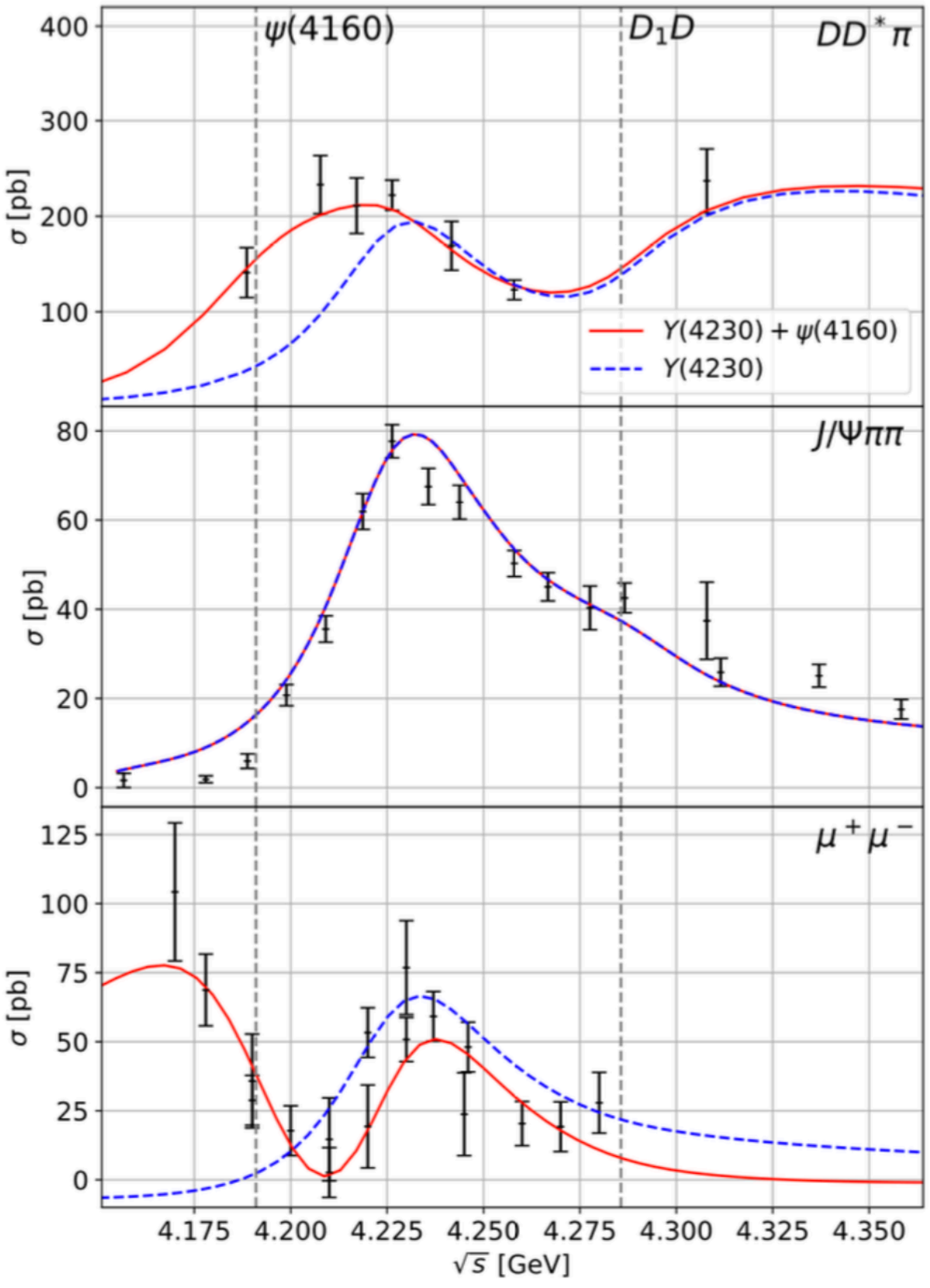
Motivation

- Goal: eight-channel global fit in the HM picture
- Disclaimers:

- The interference between $\psi(4160)$ and $Y(4230)$ perturbative
- A phenomenological study, uncontrolled uncertainties
- Neglect HQSS, i.e. do not consider $D_1\bar{D}^*$, $D_2\bar{D}^*$ channel
- Simplified $\pi\pi/K\bar{K}$ FSI Chen et al., PRD93(2016)034030, Chen et al., PRD95(2017)034022,

Baru et al., PRD103(2021)034016, Molnar et al., PLB797(2019)134851, Danilkin et al., PRD102(2020)016019

Motivation



- The requirement of $\psi(4160)$
- Describe the $DD^*\pi$ data at lower energy well
- Describe the $e^+e^- \to \mu^+\mu^-$ cross sections well
- Not strong constraint in the $J/\psi\pi\pi$ channel

Detten et al., PRD109(2024)116002

Fit parameters and strategy

- Fitted parameters

	Name	Value
Y	m_Y	(4227 ± 0.4) MeV
	g_{Y0}	$-(10.4 \pm 0.2)$ GeV
	Γ^Y_{in}	(54 ± 1) MeV
	$1/f_Y$	$-(0.012 \pm 0.001)$
	$\delta_{Y\gamma}$	$(17.1 \pm 0.1)^o$
ψ	$1/f_\psi$	$-(0.023 \pm 0.003)$
	$\delta_{\psi\gamma}$	$(67 \pm 2)^o$
Z_c	m_Z	(3884 ± 1) MeV
	g_{Z0}	(4.15 ± 0.06) GeV
	Γ^Z_{in}	(48 ± 1) MeV
$D\bar{D}^*\pi$	$\alpha_1^{(1)}$	$-(128 \pm 12)$
	$\alpha_2^{(1)}$	$-(3.95 \pm 0.01)$ GeV
	$\beta_1^{(1)}$	$-(202 \pm 18)$
	$\beta_2^{(1)}$	$-(3.89 \pm 0.1)$ GeV
$J/\psi\pi^+\pi^-$	$\alpha_1^{(2)}$	$-(133.9 \pm 4)$
	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)
	$c^{\triangle}_{\text{CT}}$	$-(0.4 \pm 0.1)$ GeV^2
	$f_{J/\psi}$	456 MeV
$\chi_{c0}\omega$	$c^{\triangle}_{\chi_{c0}\omega}$	(1.469 ± 0.015) GeV^2
	$c^{Y}_{\chi_{c0}\omega}$	$(0.36 \pm 0.07)10^{-3}$
	$c^{\psi}_{\chi_{c0}\omega}$	$-(16 \pm 0.5)10^{-3}$
$J/\psi\eta$	$c^{Y}_{J/\psi\eta}$	$(67.3 \pm 3.4)10^{-3}$ GeV^{-1}
	$c^{\psi}_{J/\psi\eta}$	$(298 \pm 11)10^{-3}$ GeV^{-1}
$X\gamma$	$c^{Y}_{X\gamma}$	(0.71 ± 0.15) GeV^2
	$c^{\psi}_{X\gamma}$	(0.017 ± 0.003) GeV
$\mu^+\mu^-$	c_{mix}	(0.6 ± 0.01)

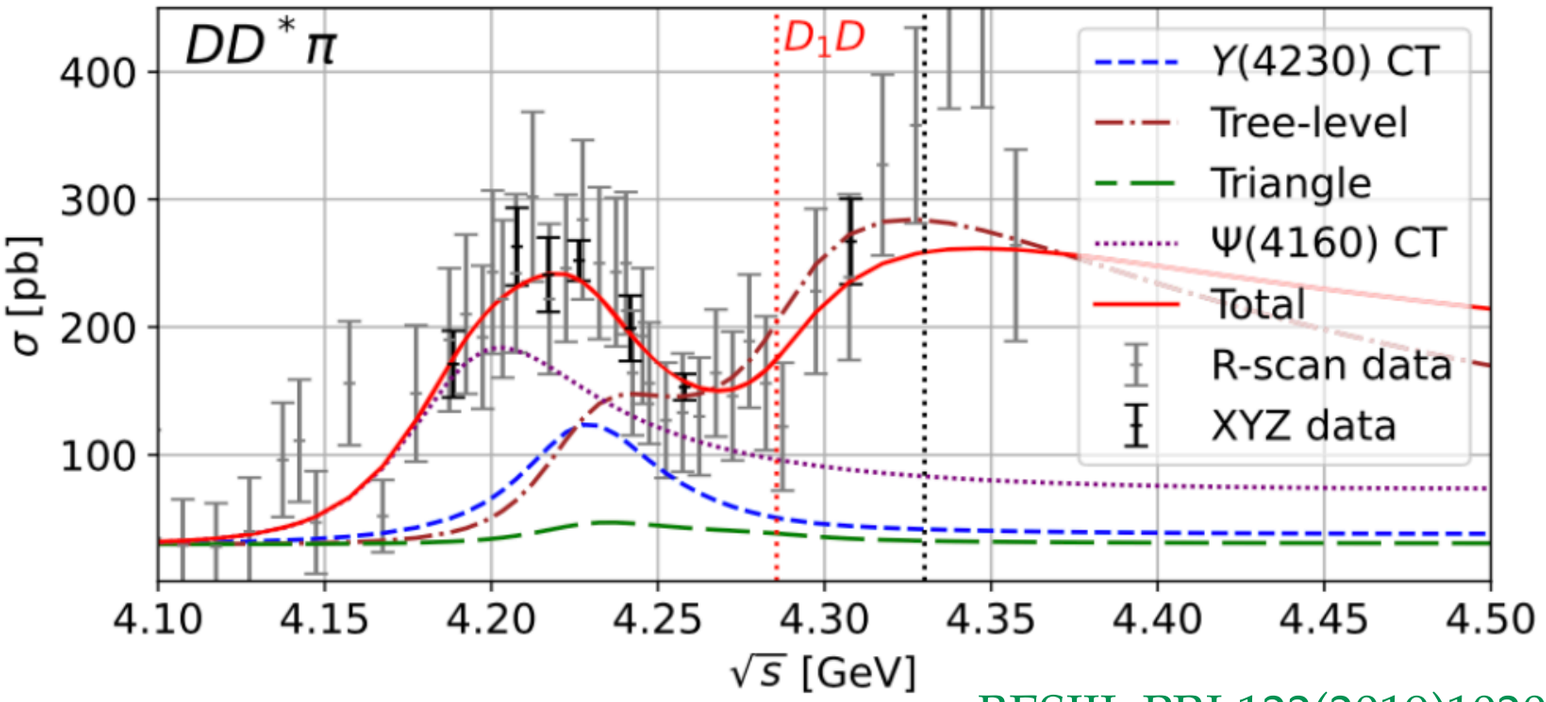
- Fit strategy

① Red parameters fitted in $D^0D^{*-}\pi^+, J/\psi\pi^+\pi^-, J/\psi K^+K^-, \mu^+\mu^-$ channels

② The remaining parameters are obtained from the $\chi_{c0}\omega, J/\psi\eta, X(3872)\gamma$ channels

The $D\bar{D}^*\pi$ channel

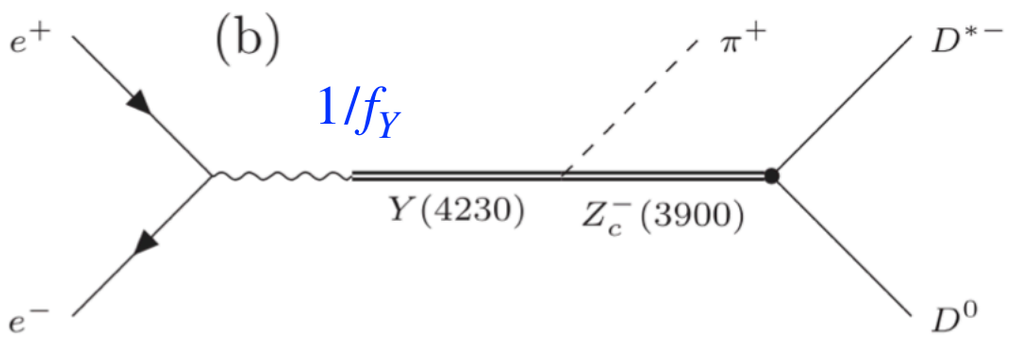
- The $D\bar{D}^*\pi$ lineshape



BESIII, PRL122(2019)102002

- $Y(4230)$ CT

respect Watson theorem



$Y(4230)$ CT

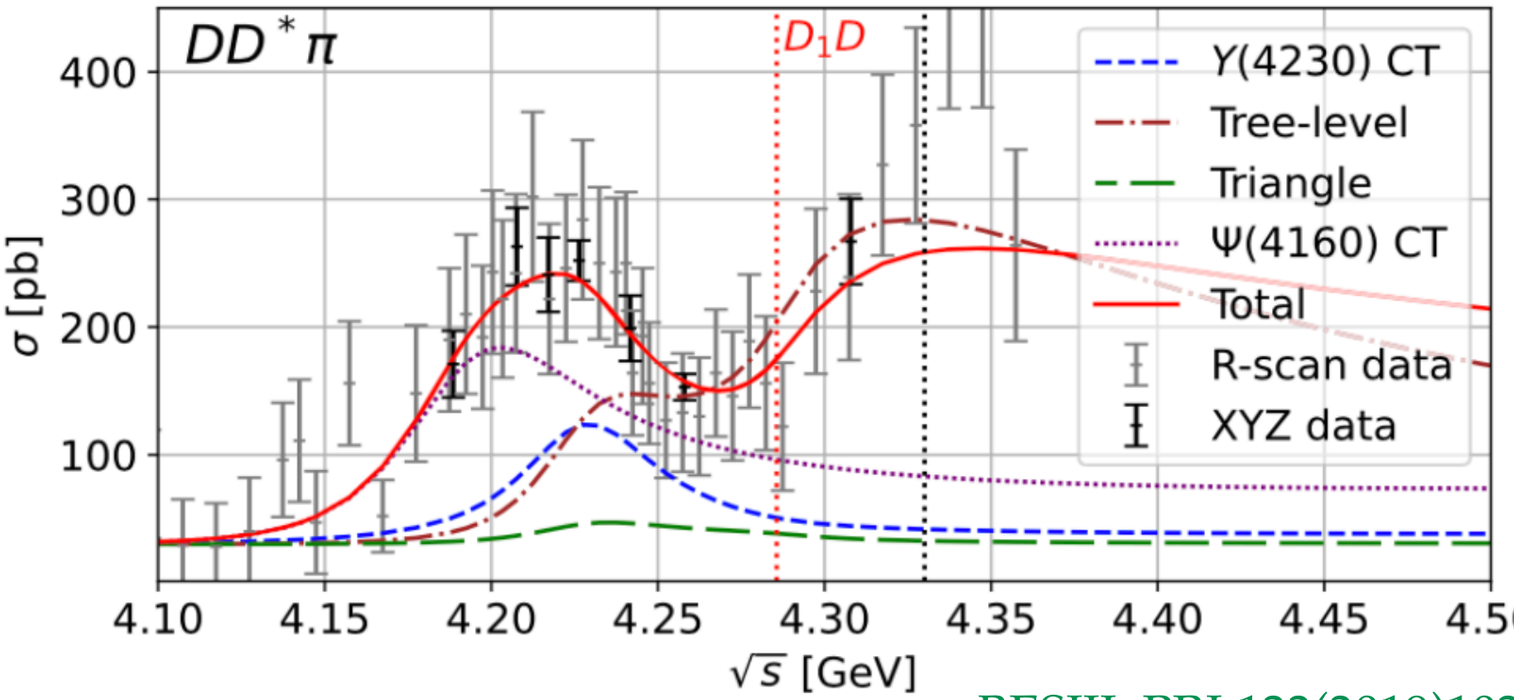
$$\left(\mathscr{M}^{DD^*\pi}_{Y\mathrm{CT}}\right)^{kj} = G_Z\left(E_{DD^*}\right) g_{Z0}\omega_\pi \left[\alpha_1^{(1)}\left(\alpha_2{}^{(1)} + E_{DD^*}\right)\delta^{kj}\right]$$

$$G_Y(E) = \frac{1}{2\omega_Y}\left(E - m_Y - g_{Y0}{}^2\Sigma_{D_1D}(E) + i\Gamma^Y_{\mathrm{in}}/2\right)^{-1}$$

m_Z g_{Z0} Γ^Z_{in}

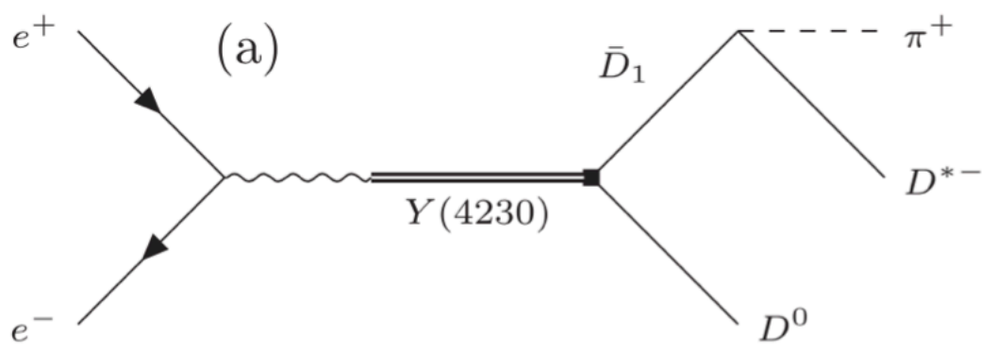
The $D\bar{D}^*\pi$ channel

- The $D\bar{D}^*\pi$ lineshape



BESIII, PRL122(2019)102002

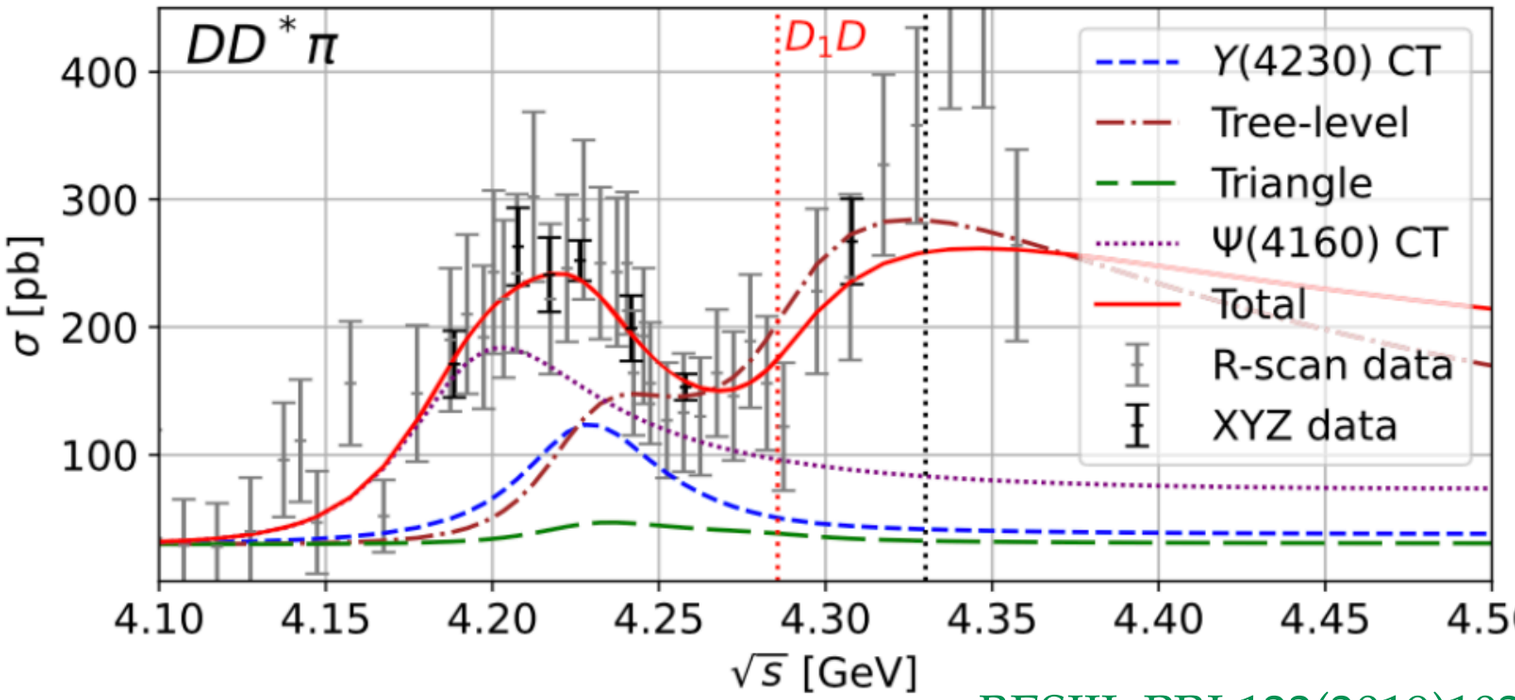
- $Y(4230)$ CT
- D_1 Tree-level



D_1 Tree-level

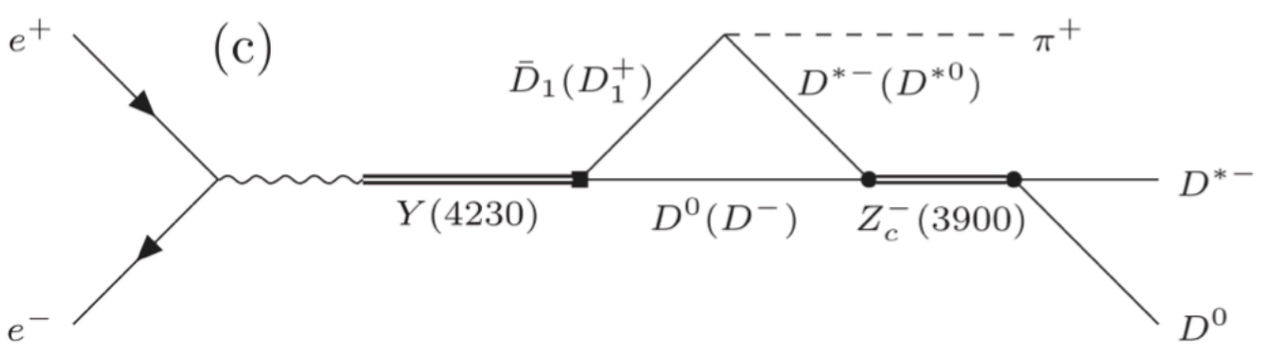
The $D\bar{D}^*\pi$ channel

- The $D\bar{D}^*\pi$ lineshape



BESIII, PRL122(2019)102002

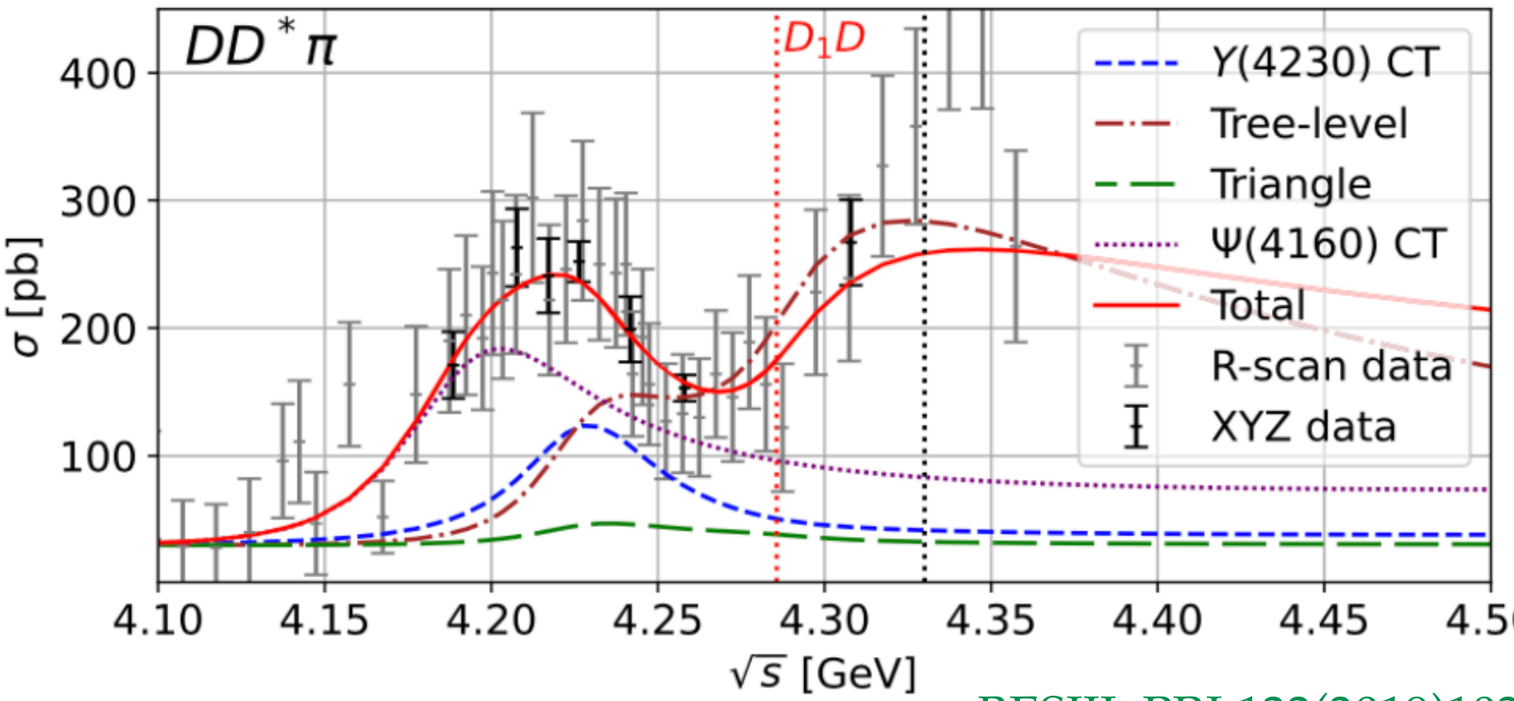
- $Y(4230)$ CT
- D_1 Tree-level
- D_1 Triangle



D_1 Triangle

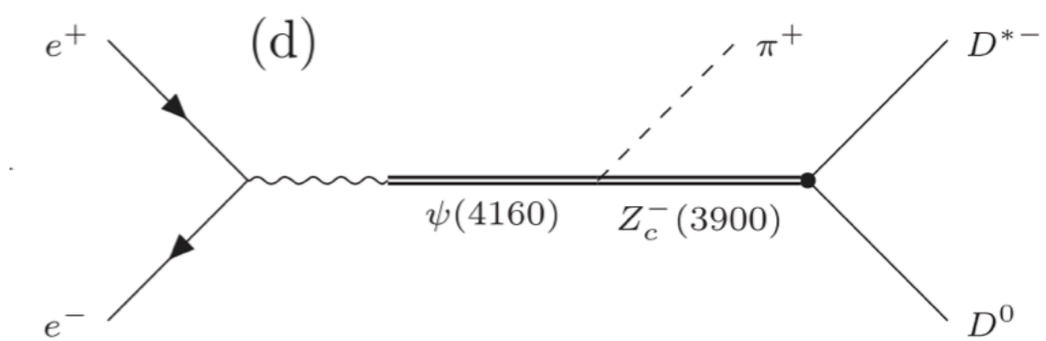
The $D\bar{D}^*\pi$ channel

- The $D\bar{D}^*\pi$ lineshape



BESIII, PRL122(2019)102002

- $Y(4230)$ CT
- D_1 Tree-level
- D_1 Triangle
- $\psi(4160)$ CT

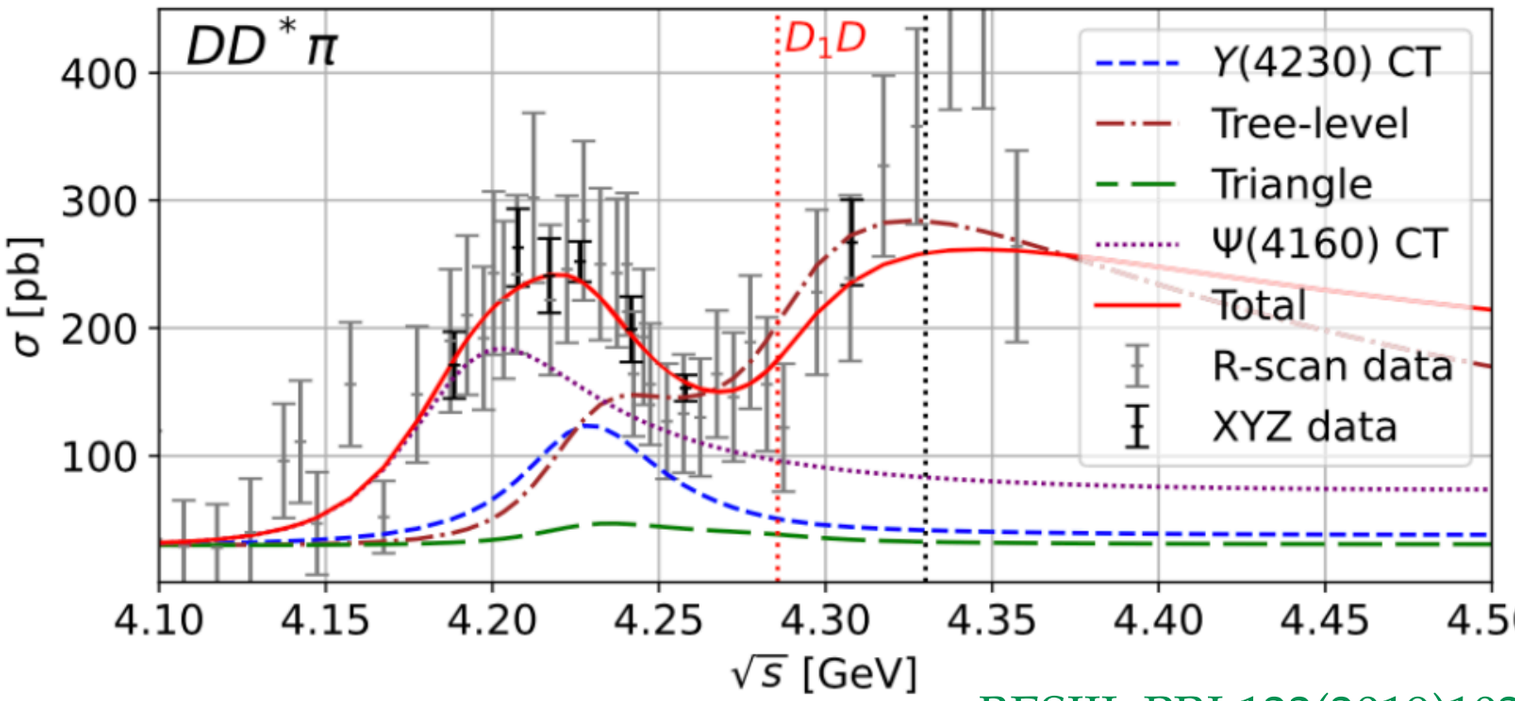


$\psi(4160)$ CT

$$\mathscr{M}^i_{\psi\to DD^*\pi} = G_\psi g_{Z0} G_Z \omega_\pi \left[\beta_1^{(1)}\left(\beta_2^{(1)} + E_{DD^*}\right)\delta^{ij}\right]\epsilon^{*j}_{D^*}$$

The $D\bar{D}^*\pi$ channel

- The $D\bar{D}^*\pi$ lineshape



- $Y(4230)$ CT
- D_1 Tree-level
- D_1 Triangle
- $\psi(4160)$ CT

BESIII, PRL122(2019)102002

① Significant $D_1\bar{D}$ threshold effect from both tree-level and triangle diagrams

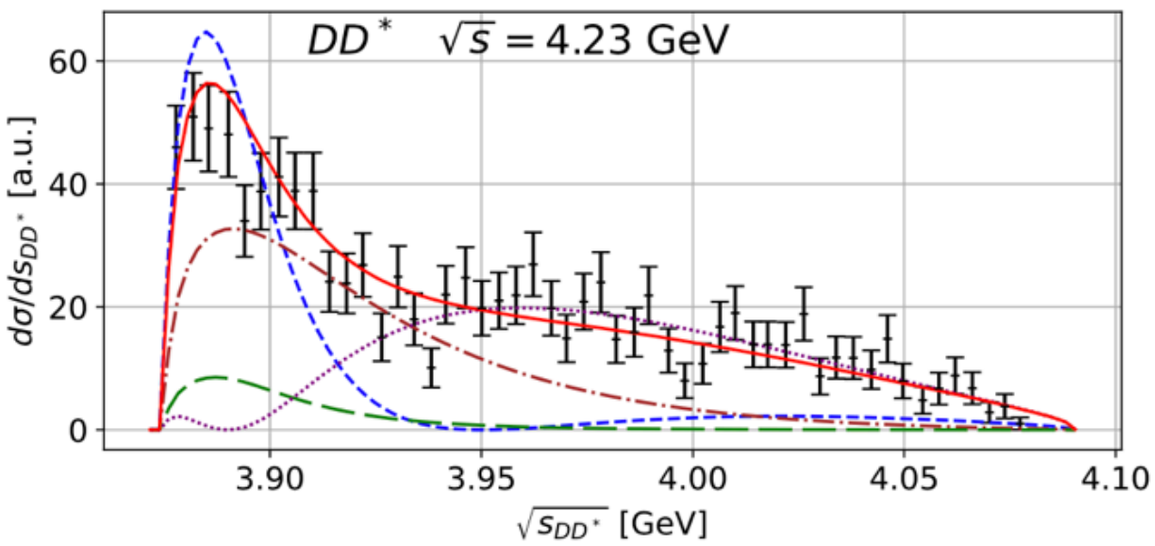
② Pole of Y(4230) is $(4227 \pm 4) - (25^{+4}_{-1})i$ MeV with uncertainty from the g_{Y_0}, m_0, Γ_{in} constrained by the $J/\psi\pi\pi$ channel

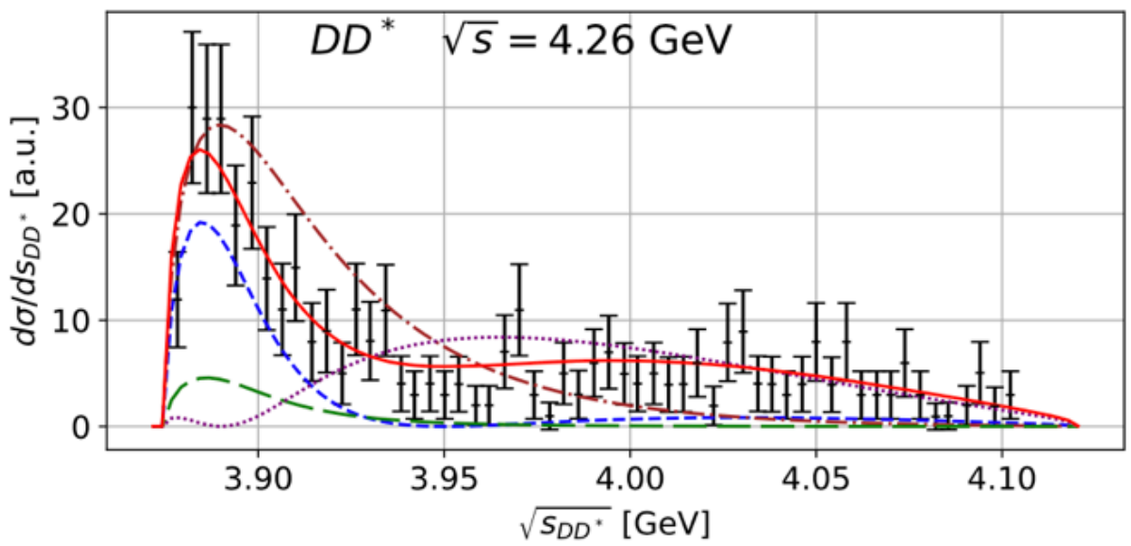
③ Pole of $Z_c(3900)$ is $3884 - 22i$ MeV , higher mass and double width compare to that in

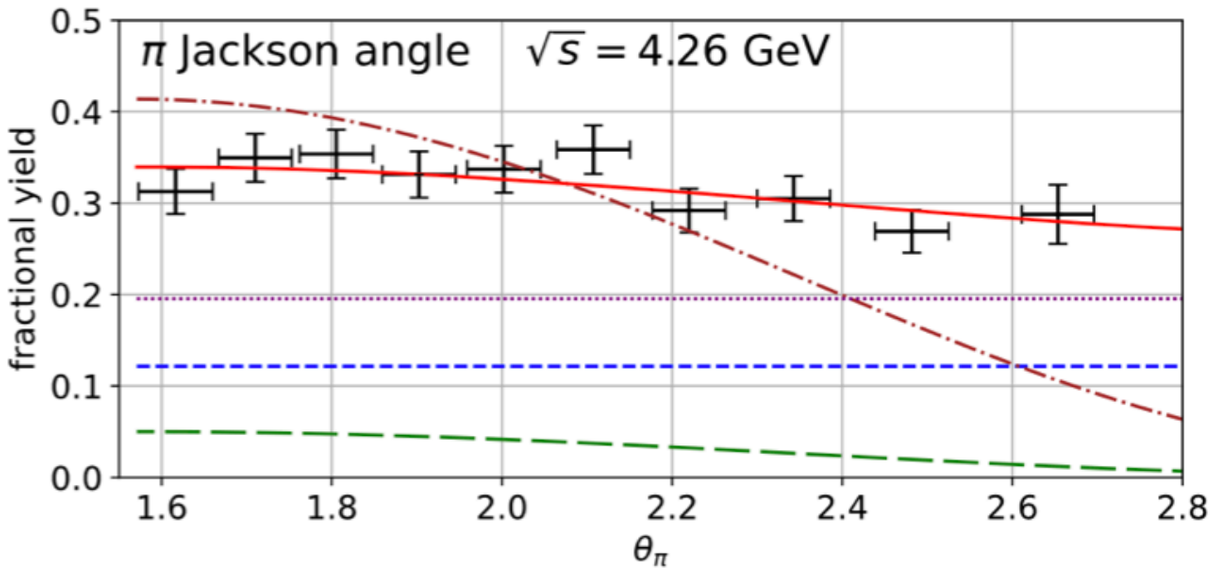
Chen et al., arXiv:2310.15965

The $D\bar{D}^*\pi$ channel

- The subsystem lineshape







BESIII, PRD92(2015)092006

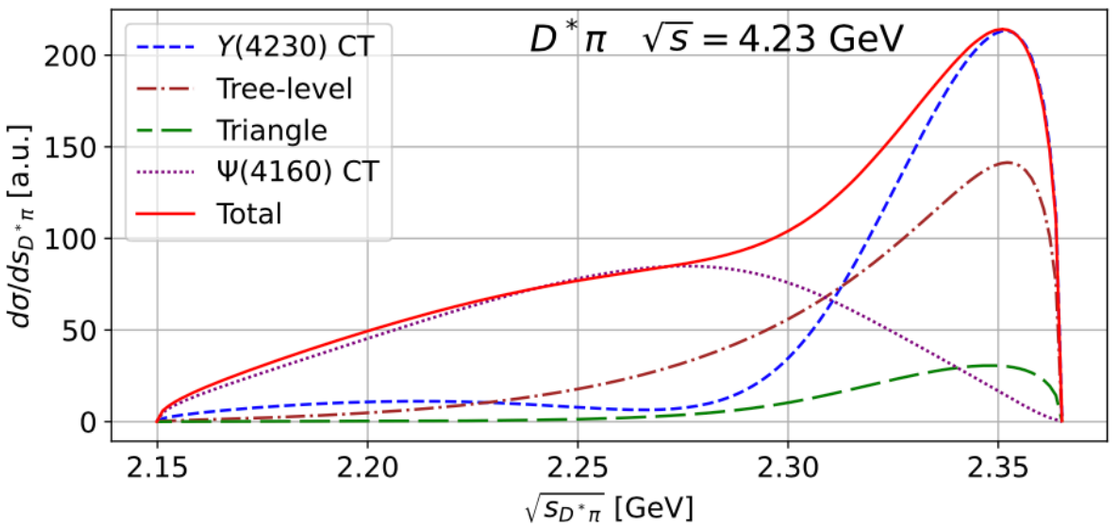
① Constraints from subsystems

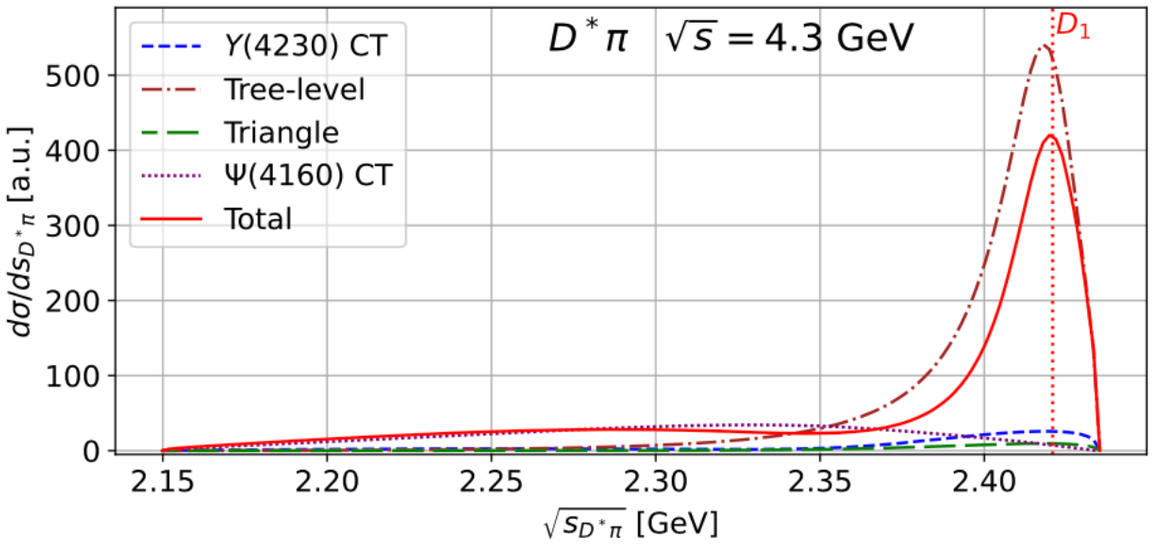
② Both Z_c and D_1 give enhancement at lower $M_{D\bar{D}^*}$ and higher $M_{\bar{D}^*\pi}$

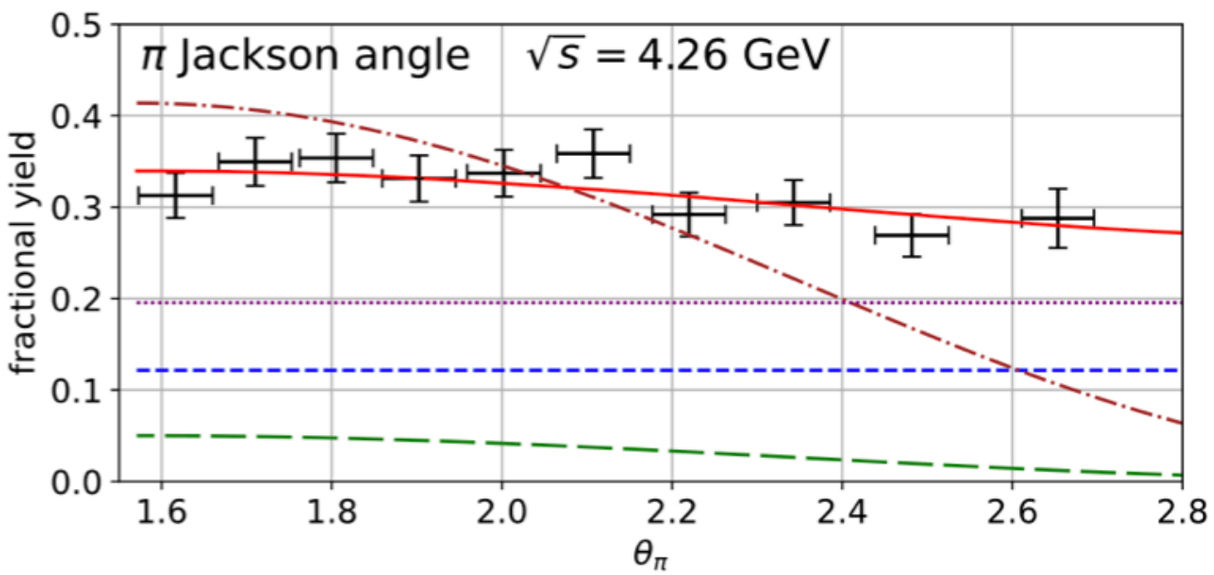
③ The total contribution of D-wave and S-wave give flat pion angular distribution

The $D\bar{D}^*\pi$ channel

- The subsystem lineshape







BESIII, PRD92(2015)092006

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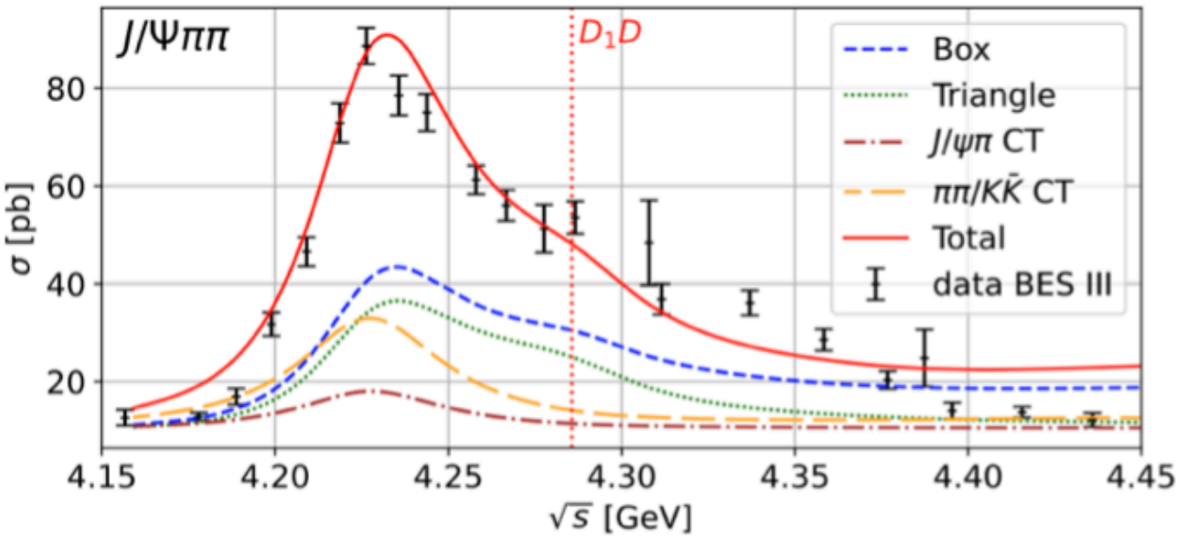
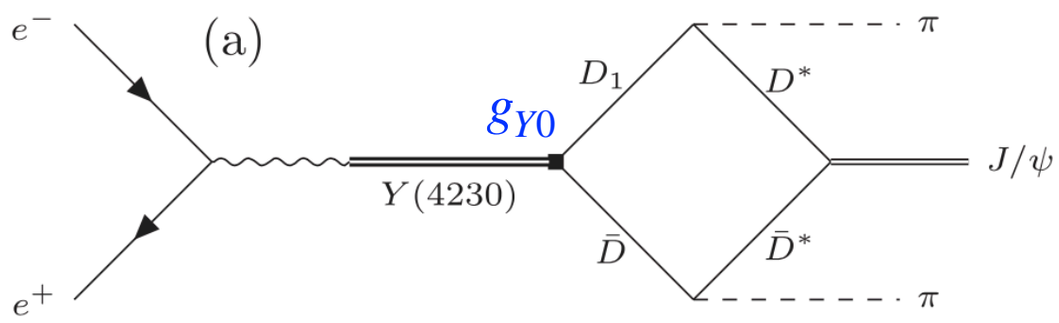
The $J/\psi\pi\pi$ channel

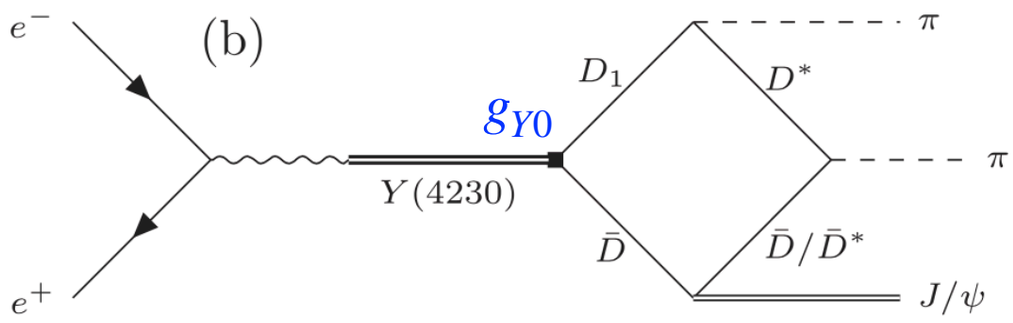
- The $J/\psi\pi\pi$ line shapes



BESIII, PRD106(2022)072001

- Box

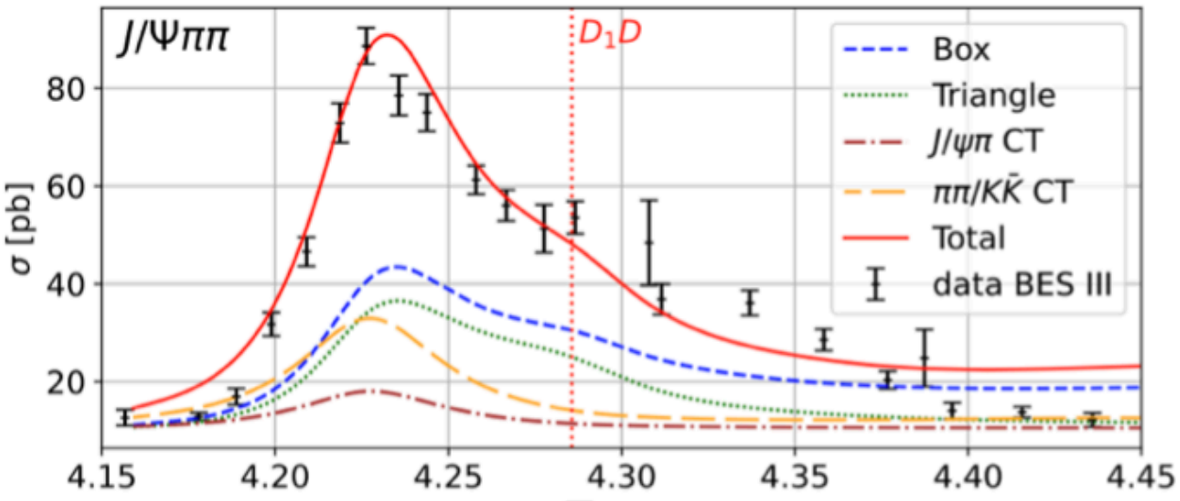




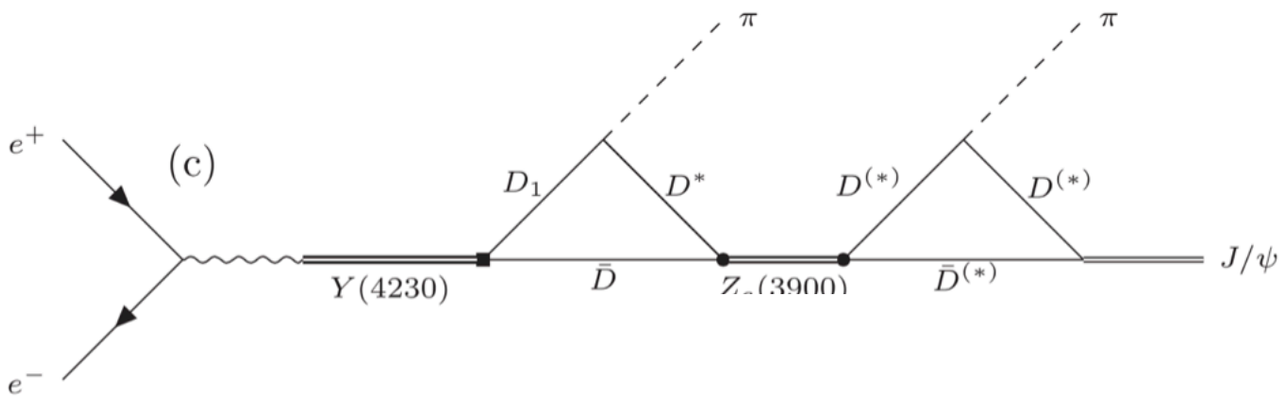
Box

The $J/\psi\pi\pi$ channel

- The $J/\psi\pi\pi$ line shapes



BESIII, PRD106(2022)072001

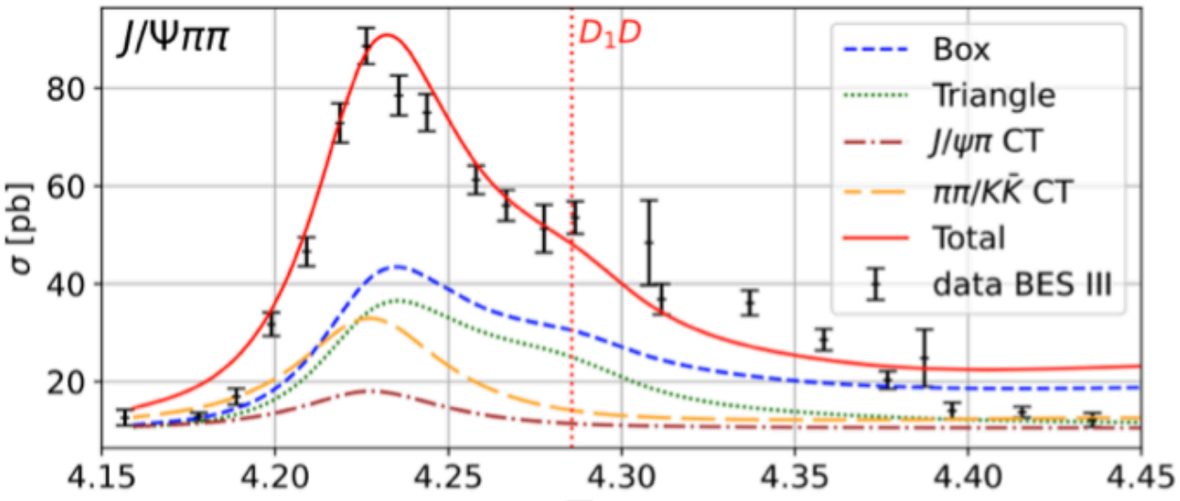


- Box
- Triangle

Triangle

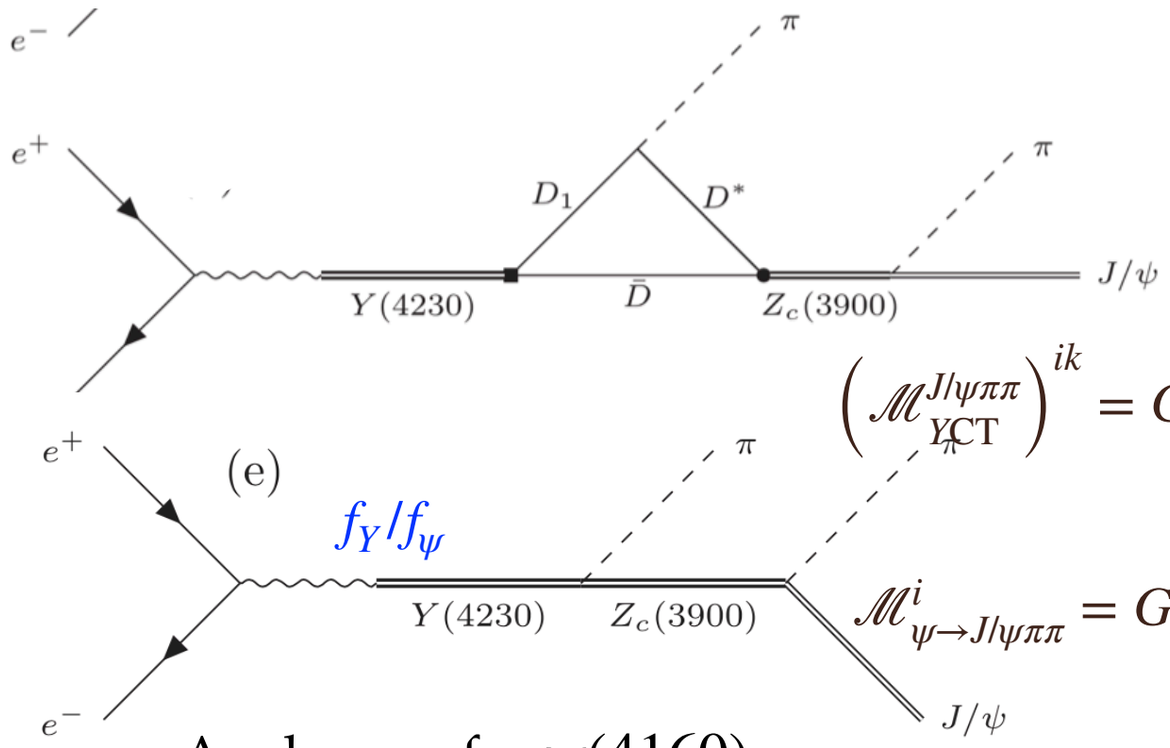
The $J/\psi\pi\pi$ channel

- The $J/\psi\pi\pi$ line shapes



BESIII, PRD106(2022)072001

- Box
- Triangle
- $J/\psi\pi$ CT



Analogous for $\psi(4160)$

$J/\psi\pi$ CT

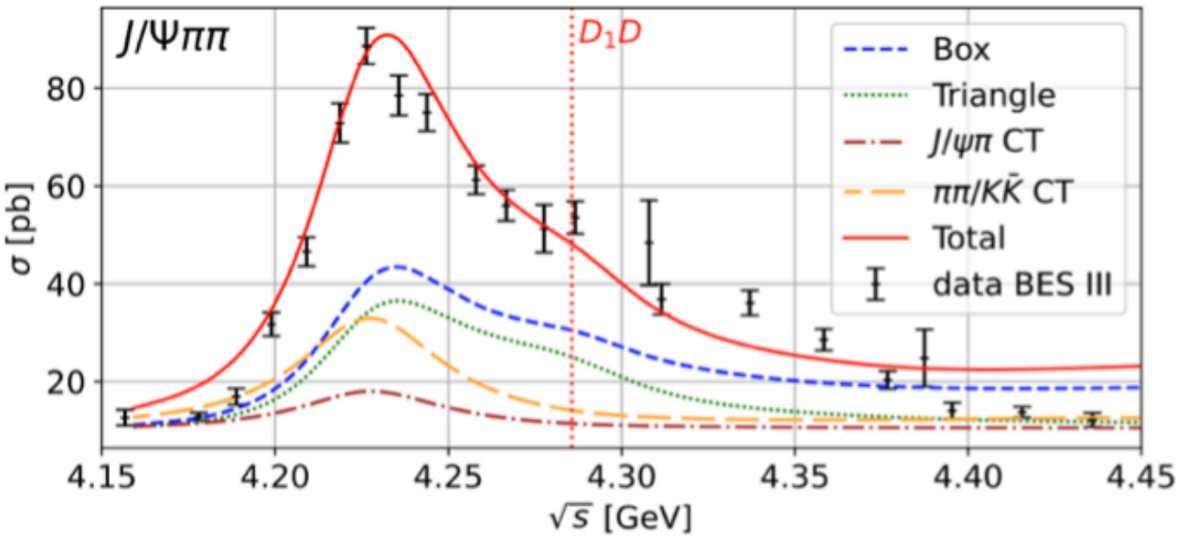
$$g^{Z_c ik}_{J/\psi\pi} = g_{Z0}\left(\mathscr{M}^{\triangle}_{2}\right)^{ik} + \omega_{\pi_2} c^{\triangle}_{\mathrm{CT}} \delta^{ik}$$

$$\left(\mathscr{M}^{J/\psi\pi\pi}_{Y_\pi \mathrm{CT}}\right)^{ik} = G_Z g^{Zik}_{J/\psi\pi}\omega_{\pi_1}\left[\alpha^{(2)}_1\left(\alpha^{(2)}_2 + E_{J/\psi\pi}\right)\right] + \Omega_{11}M_0^{\pi\pi} + \frac{2}{\sqrt{3}}\Omega_{12}M_0^{KK}$$

$$\mathscr{M}^{i}_{\psi\to J/\psi\pi\pi} = G_\psi\left[\beta^{(2)}_1\left(\beta^{(2)}_2 + E_{J/\psi\pi_1}\right)\right] g^{Zil}_{J/\psi\pi}\omega_{\pi_1} G_Z\left(E_{J/\psi\pi_1}\right)\epsilon^{*l}_{J/\psi} + \left(p_{\pi_1} \leftrightarrow p_{\pi_2}\right)$$

The $J/\psi\pi\pi$ channel

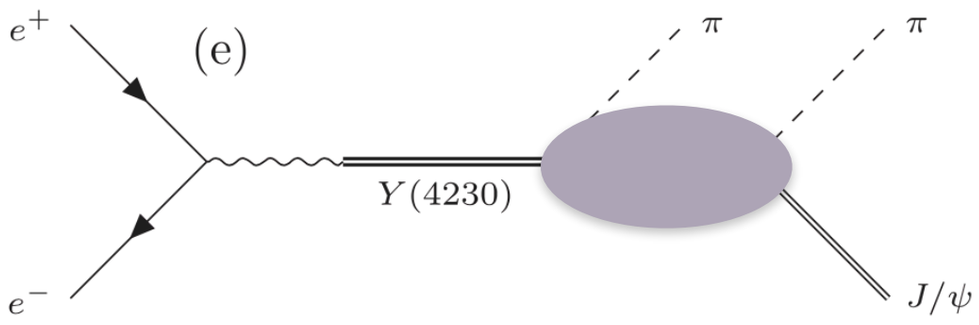
- The $J/\psi\pi\pi$ line shapes



BESIII, PRD106(2022)072001

- Box
- Triangle
- $J/\psi\pi$ CT
- $\pi\pi, K\bar{K}$ CT

$\pi\pi, K\bar{K}$ CT



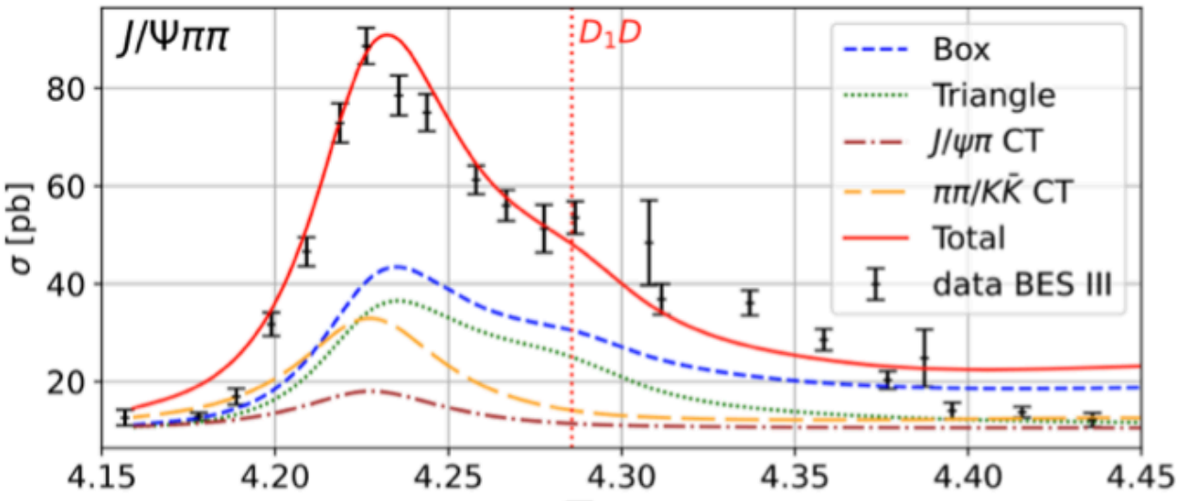
$$\mathscr{L}_{Y\psi\phi\phi} = g_1 \left\langle V_1^\alpha J_\alpha^\dagger \right\rangle \left\langle u_\mu u^\mu \right\rangle + h_1 \left\langle V_1^\alpha J_\alpha^\dagger \right\rangle \left\langle u_\mu u_\nu \right\rangle v^\mu v^\nu + g_8 \left\langle J_\alpha^\dagger \right\rangle \left\langle V_8^\alpha u_\mu u^\mu \right\rangle + h_8 \left\langle J_\alpha^\dagger \right\rangle \left\langle V_8^\alpha u_\mu u_\nu \right\rangle v^\mu v^\nu + \mathrm{H.c.}$$

Isken et al., EPJC77(2017)489

$$\left(\mathscr{M}_{\mathrm{YCT}}^{J/\psi\pi\pi}\right)^{ik} = G_Z g_{J/\psi\pi}^{Zik} \omega_{\pi_1} \left[\alpha_1^{(2)} \left(\alpha_2^{(2)} + E_{J/\psi\pi}\right)\right] + \Omega_{11} M_0^{\pi\pi} + \frac{2}{\sqrt{3}} \Omega_{12} M_0^{KK}$$

The $J/\psi\pi\pi$ channel

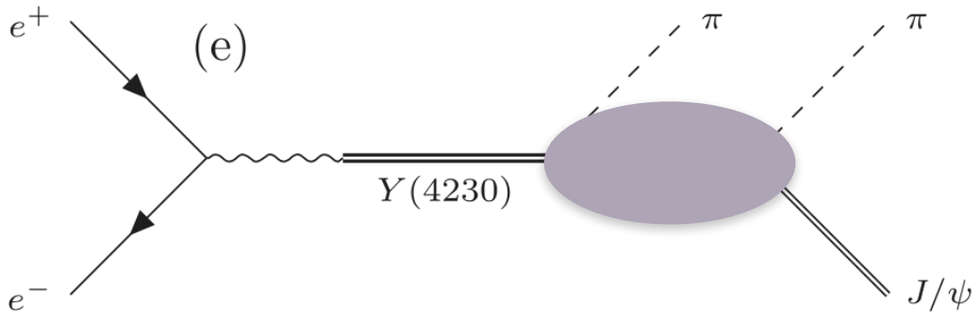
- The $J/\psi\pi\pi$ line shapes



BESIII, PRD106(2022)072001

- Box
- Triangle
- $J/\psi\pi$ CT
- $\pi\pi, K\bar{K}$ CT

$\pi\pi, K\bar{K}$ CT

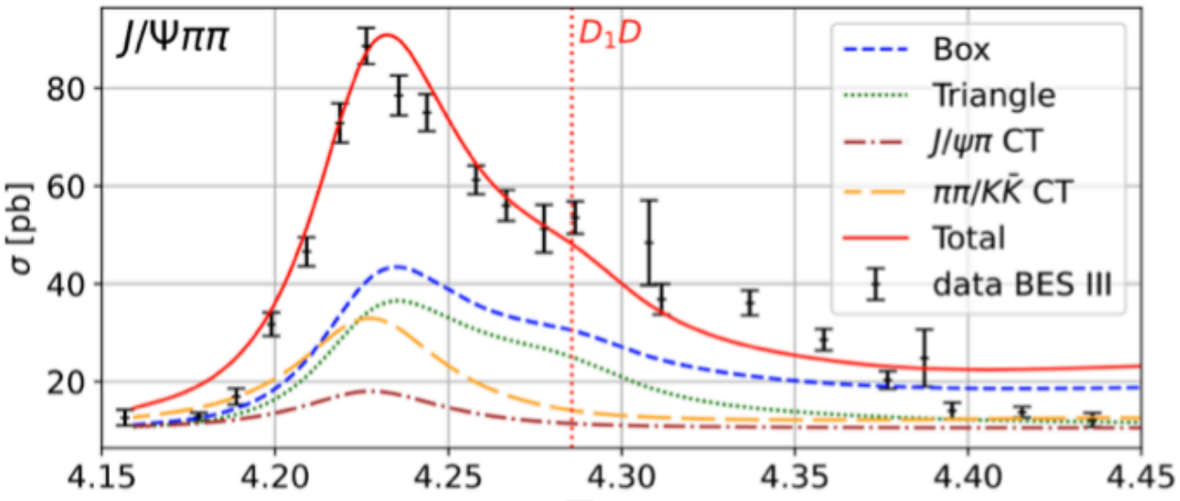


$$M_0^{\pi\pi} = -\frac{2}{f^2}\sqrt{m_Y m_{J/\psi}}\left(g_1+\frac{g_8}{\sqrt{2}}\right)(s-2m_\pi^2)+\frac{h_1+\frac{h_8}{\sqrt{2}}}{2}\left[s+q^2\left(1-\frac{\sigma_\pi}{3}\right)\right]$$

$$\left(\mathscr{M}^{J/\psi\pi\pi}_{\mathrm{YCT}}\right)^{ik} = G_Z g^{Zik}_{J/\psi\pi}\omega_{\pi_1}\left[\alpha_1^{(2)}\left(\alpha_2^{(2)}+E_{J/\psi\pi}\right)\right]+\Omega_{11}M_0^{\pi\pi}+\frac{2}{\sqrt{3}}\Omega_{12}M_0^{KK}$$

The $J/\psi\pi\pi$ channel

- The $J/\psi\pi\pi$ line shapes



BESIII, PRD106(2022)072001

- Box
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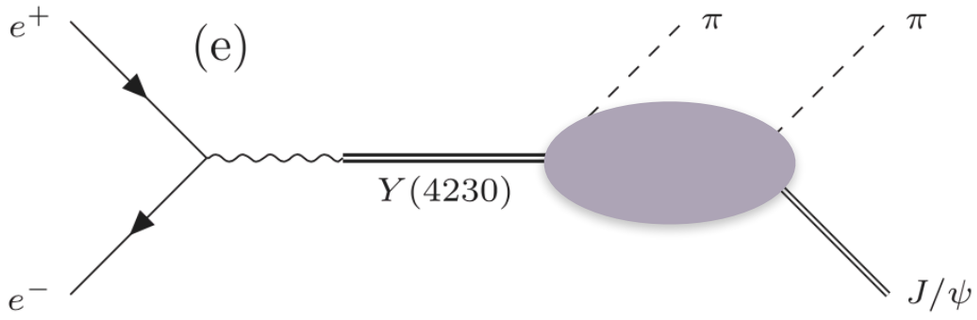
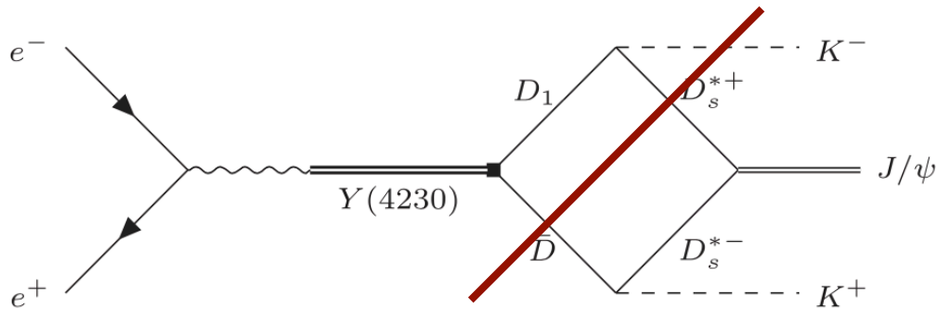
$\pi\pi, K\bar{K}$ CT



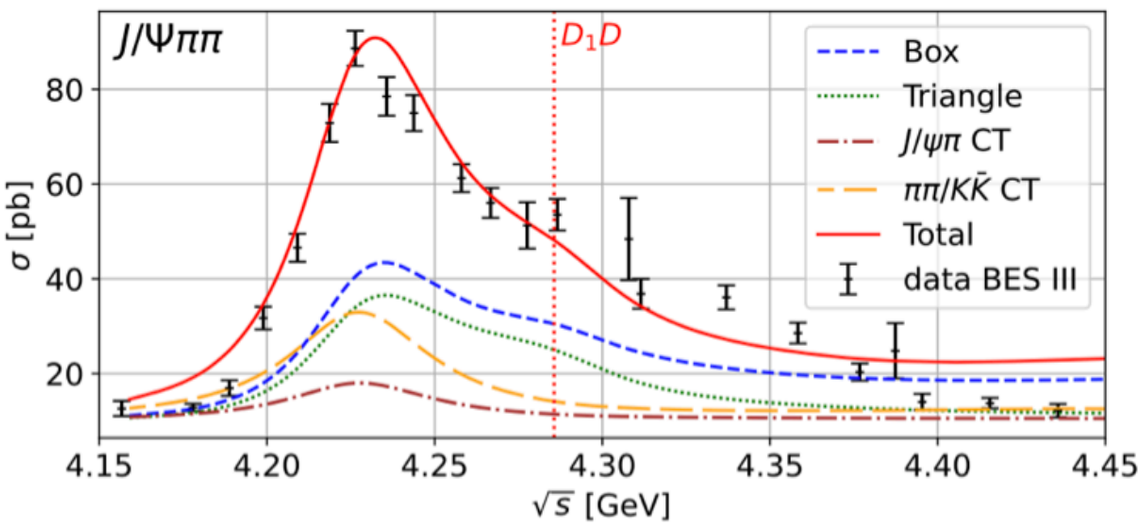
$$M_0^{KK} = -\frac{2}{f^2}\sqrt{m_Y m_{J/\psi}}\left(g_1 - \frac{g_8}{2\sqrt{2}}\right)(s-2m_K^2) + \frac{h_1 - \frac{h_8}{2\sqrt{2}}}{2}\left[s + q^2\left(1-\frac{\sigma_K}{3}\right)\right]$$

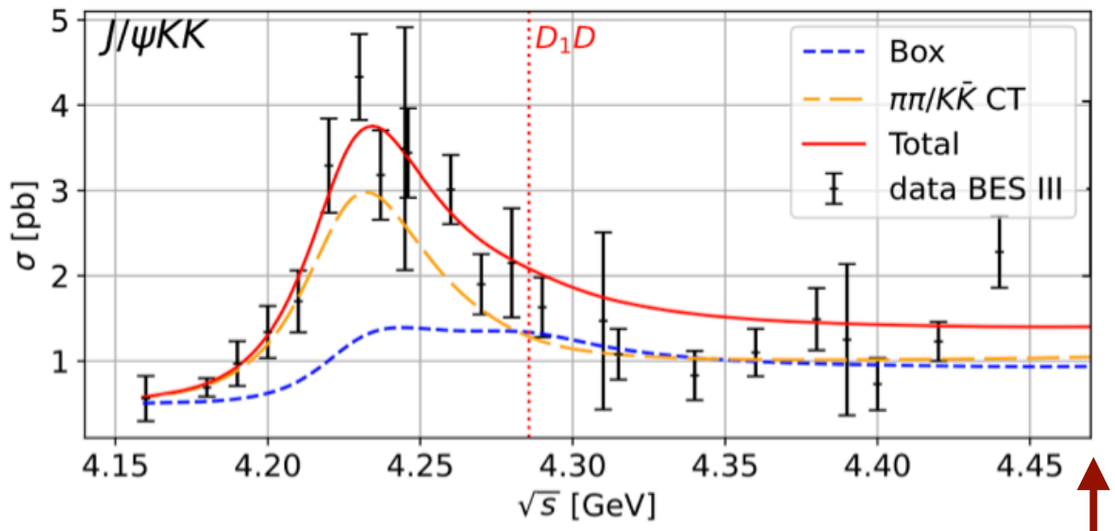
$$\left(\mathscr{M}^{J/\psi\pi\pi}_{\mathrm{YCT}}\right)^{ik} = G_Z g^{Zik}_{J/\psi\pi}\omega_{\pi_1}\left[\alpha_1^{(2)}\left(\alpha_2^{(2)} + E_{J/\psi\pi}\right)\right] + \Omega_{11}M_0^{\pi\pi} + \frac{2}{\sqrt{3}}\Omega_{12}M_0^{KK}$$

The $J/\psi\pi\pi$, $J/\psi K\bar{K}$ channels



- The $J/\psi\pi\pi$, $J/\psi K\bar{K}$ line shapes





BESIII, PRD106(2022)072001 BESIII, CPC46(2022)111002

$D_s^{*+}\bar{D}K^-$

① Asymmetric lineshape from $D_1\bar{D}$ threshold, i.e. Box and Triangle

② Strange source, but no Z_{cs}, for $J/\psi K\bar{K}$ channel

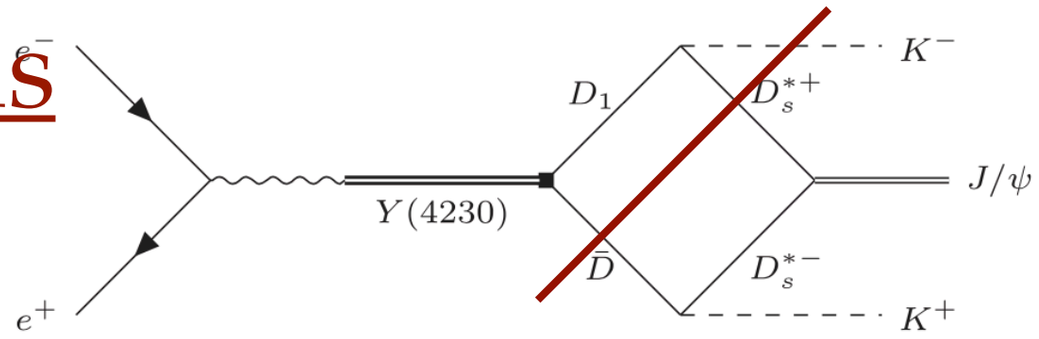
③ The leading effect is driven by the $\pi\pi/K\bar{K}$ FSI for the $J/\psi K\bar{K}$ channel

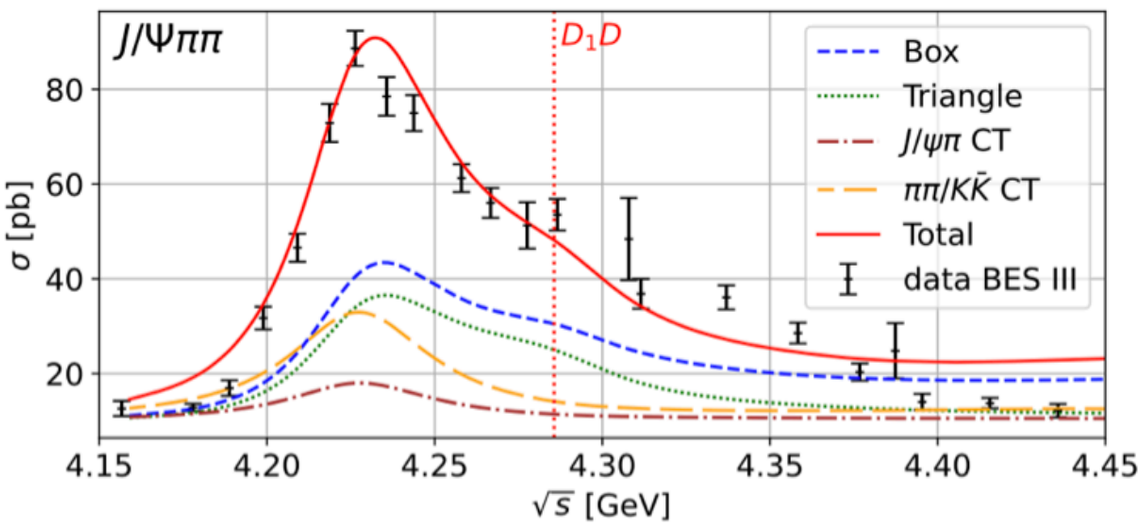
④ Energy goes beyond the $D_s^{*+}\bar{D}K^-$ threshold, the strange source is important

⑤ Describe the lineshape of the subsystems

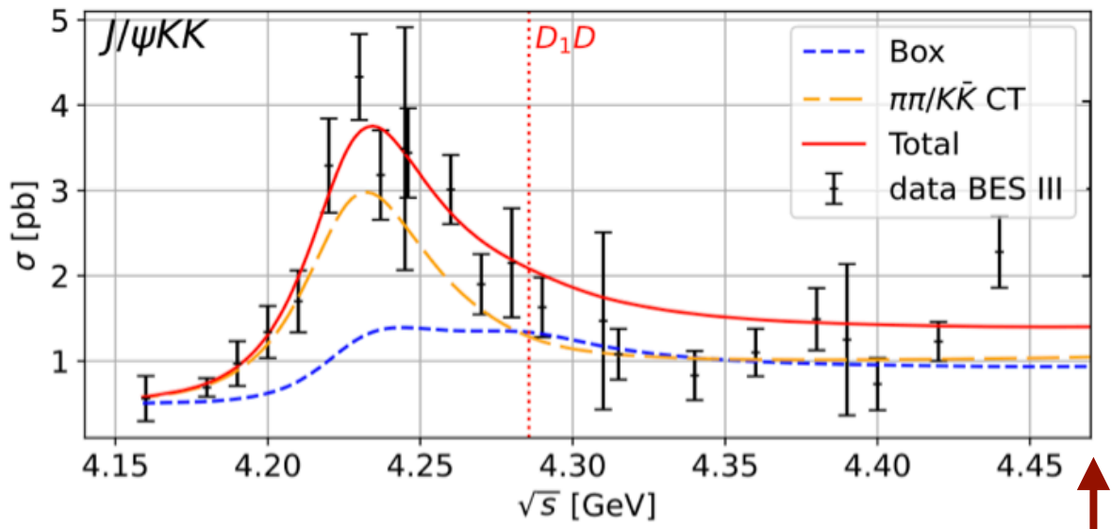
The $J/\psi\pi\pi$, $J/\psi K\bar{K}$ channels

- The $J/\psi\pi\pi$, $J/\psi K\bar{K}$ line shapes



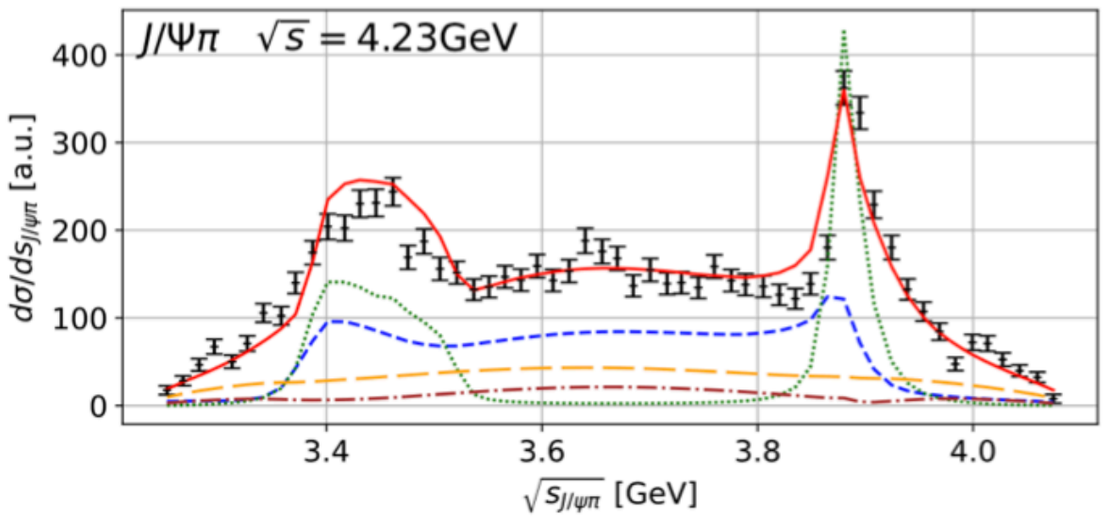


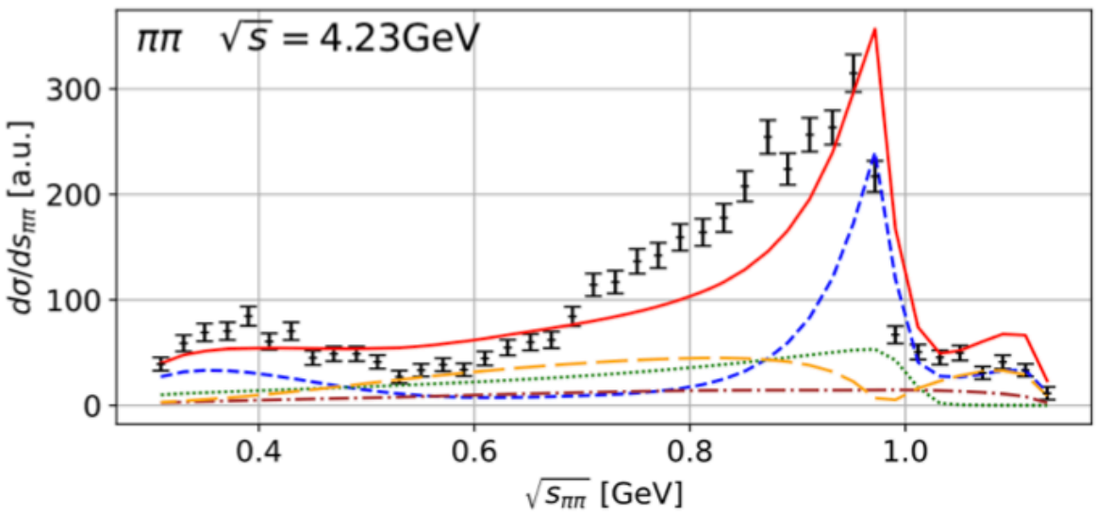
BESIII, PRD106(2022)072001



BESIII, CPC46(2022)111002

$D_s^{*+}\bar{D}K^-$

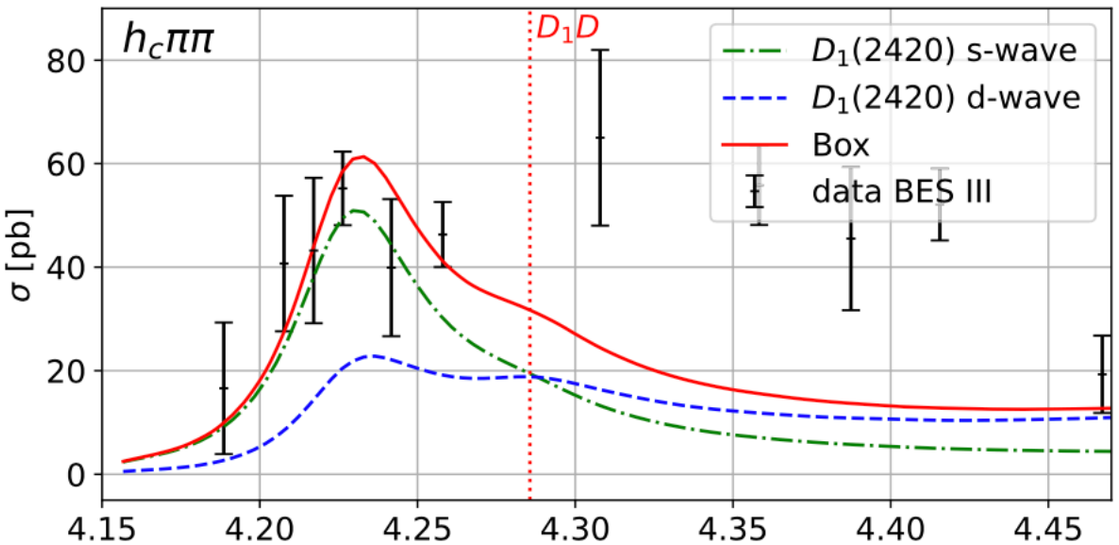




BESIII, PRL119(2017)072001

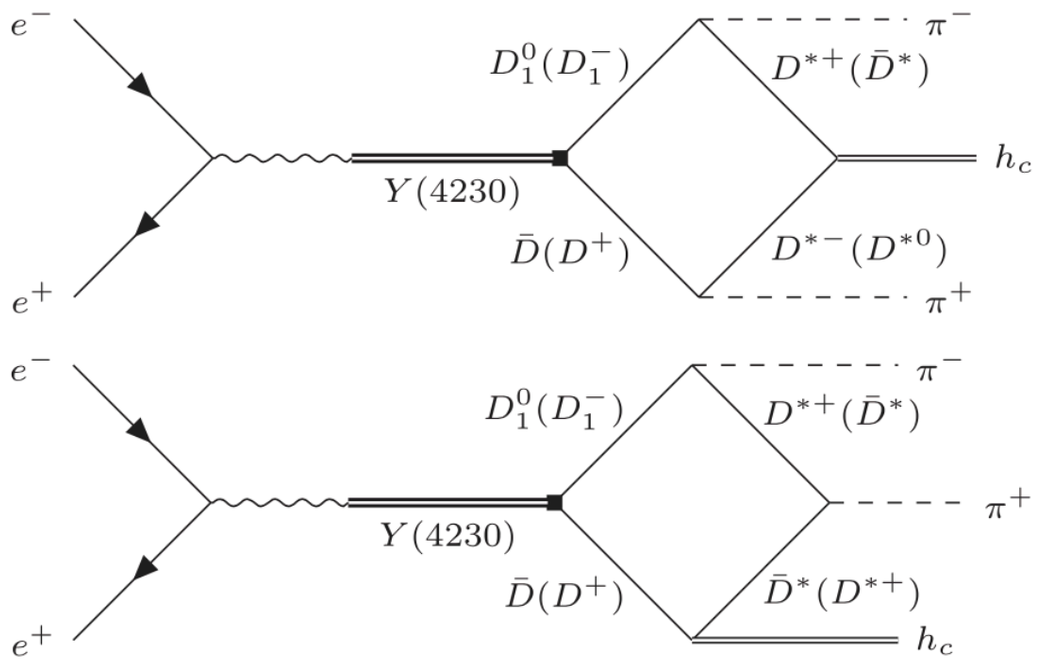
The $h_c\pi\pi$ channel

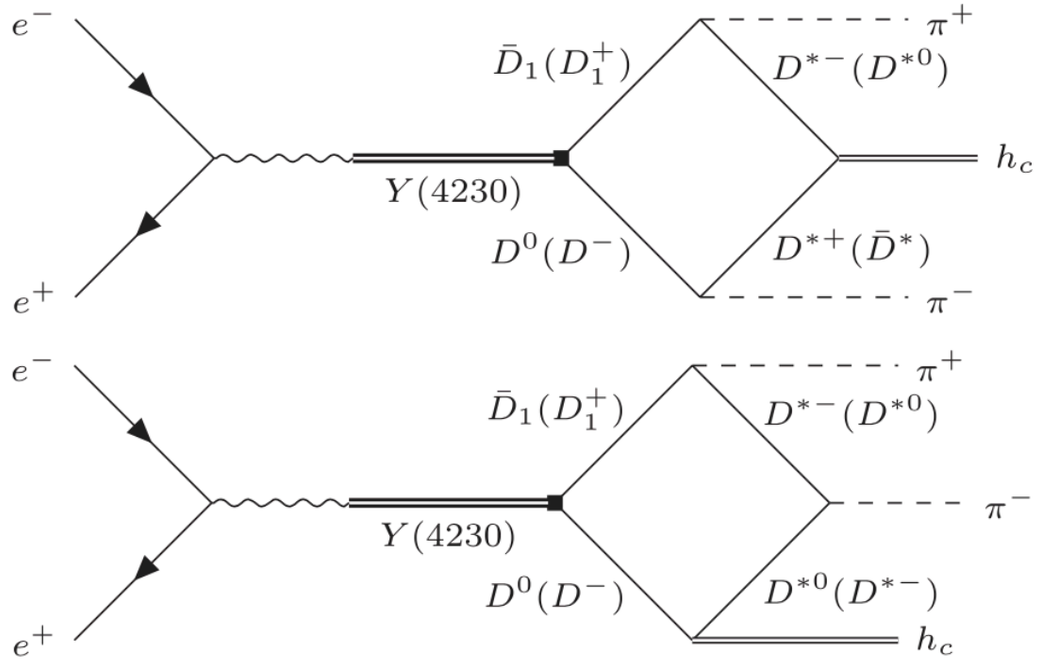
- The $h_c\pi\pi$ line shapes



- D-wave D_1
- S-wave D_1

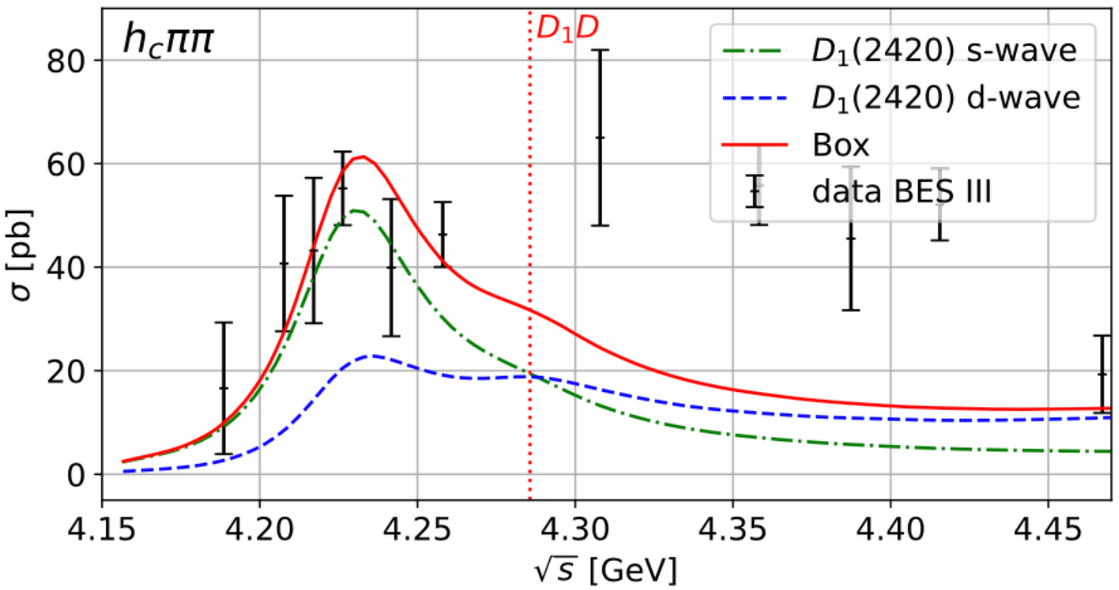
BESIII, PRL118(2017)092002





The $h_c\pi\pi$ channel

- The $h_c\pi\pi$ line shapes



BESIII, PRL118(2017)092002

- D-wave D_1
- S-wave D_1

① No $Z_c(3900)$ observed in $h_c\pi$ channel, only consider box diagram

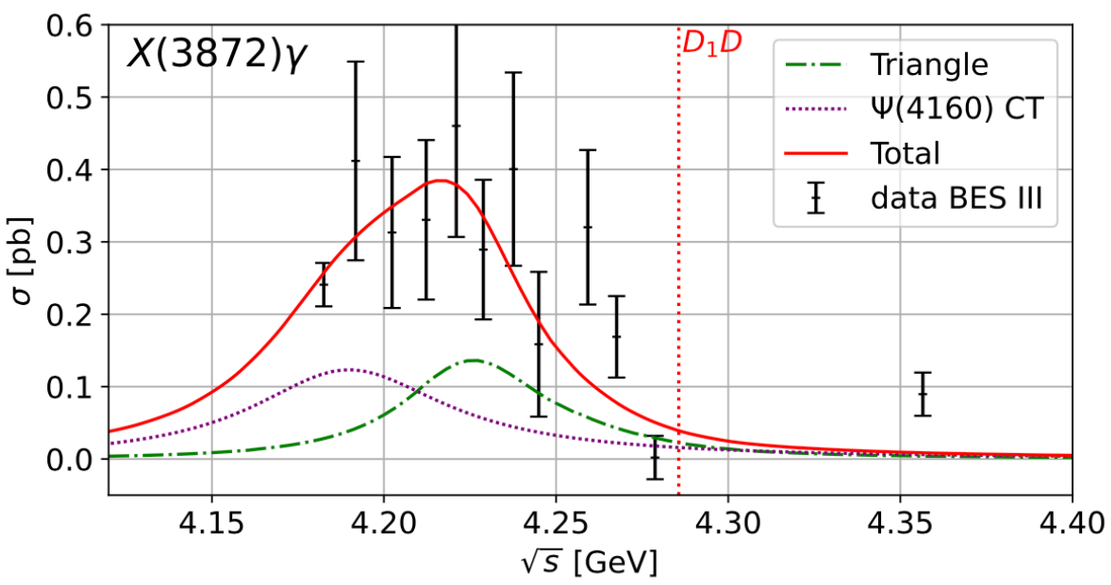
② No S-wave $\pi\pi$ FSI

③ Cross section is with the same order as that of the $J/\psi\pi\pi$ channel

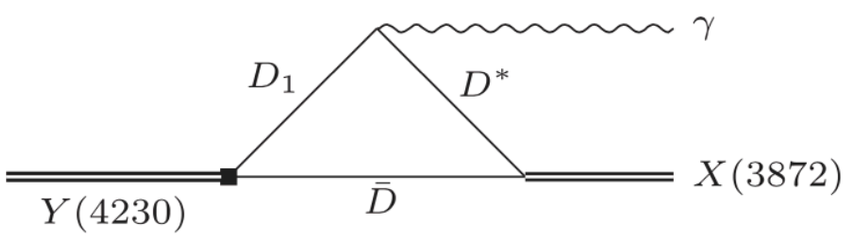
④ Large HQSS violation is accepted in HM picture naturally

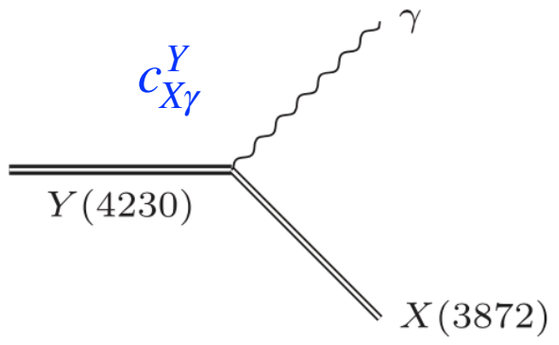
The $J/\psi\eta$, $\chi_{c0}\omega$, $X(3872)\gamma$ channels

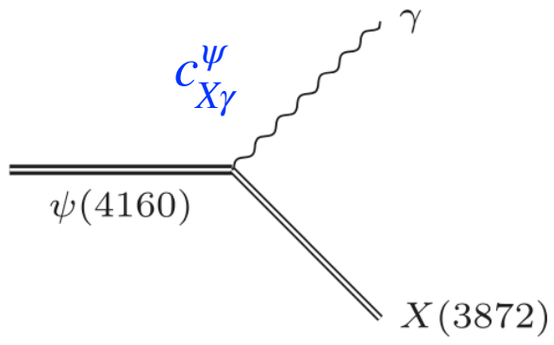
- The $J/\psi\eta$, $\chi_{c0}\omega$, $X(3872)\gamma$ line shapes



BESIII, PRL122(2019)232002

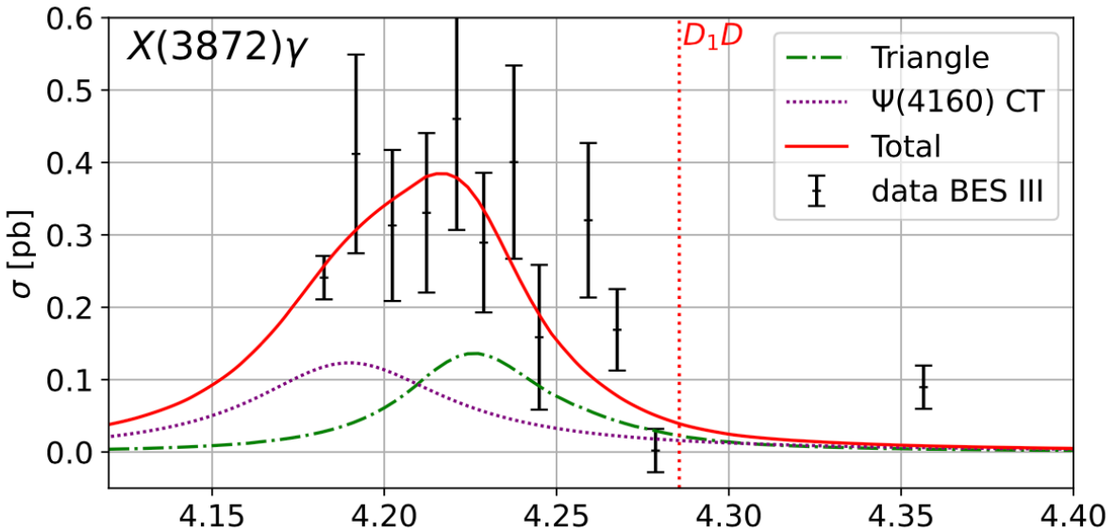




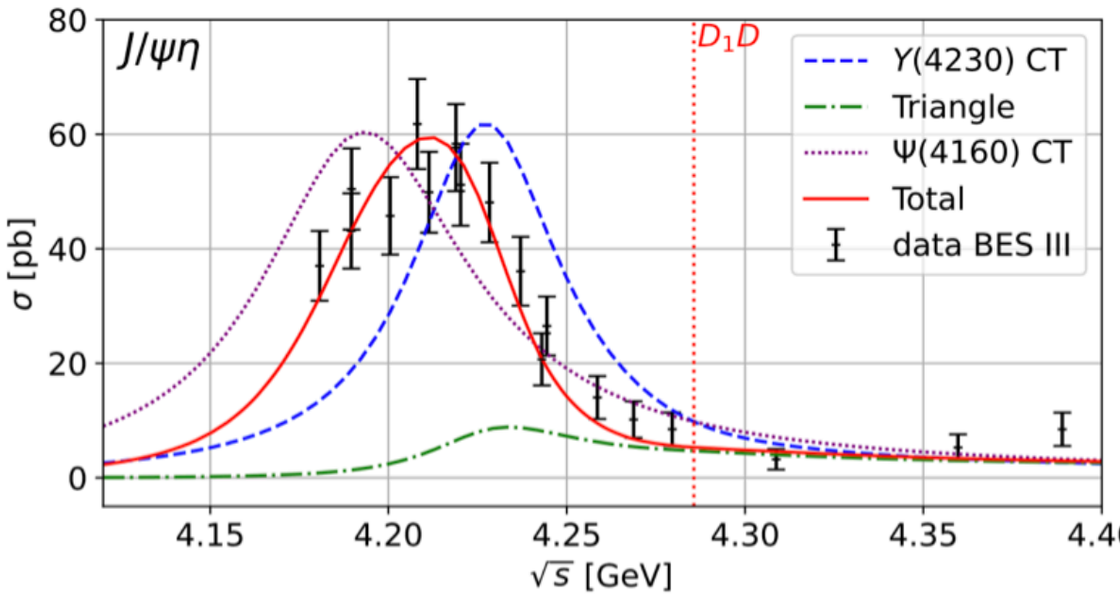


The $J/\psi\eta$, $\chi_{c0}\omega$, $X(3872)\gamma$ channels

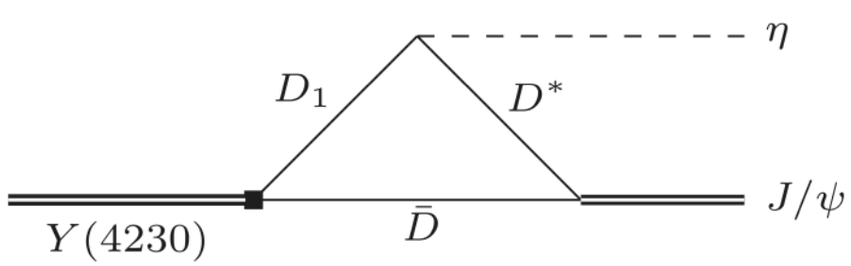
- The $J/\psi\eta$, $\chi_{c0}\omega$, $X(3872)\gamma$ line shapes

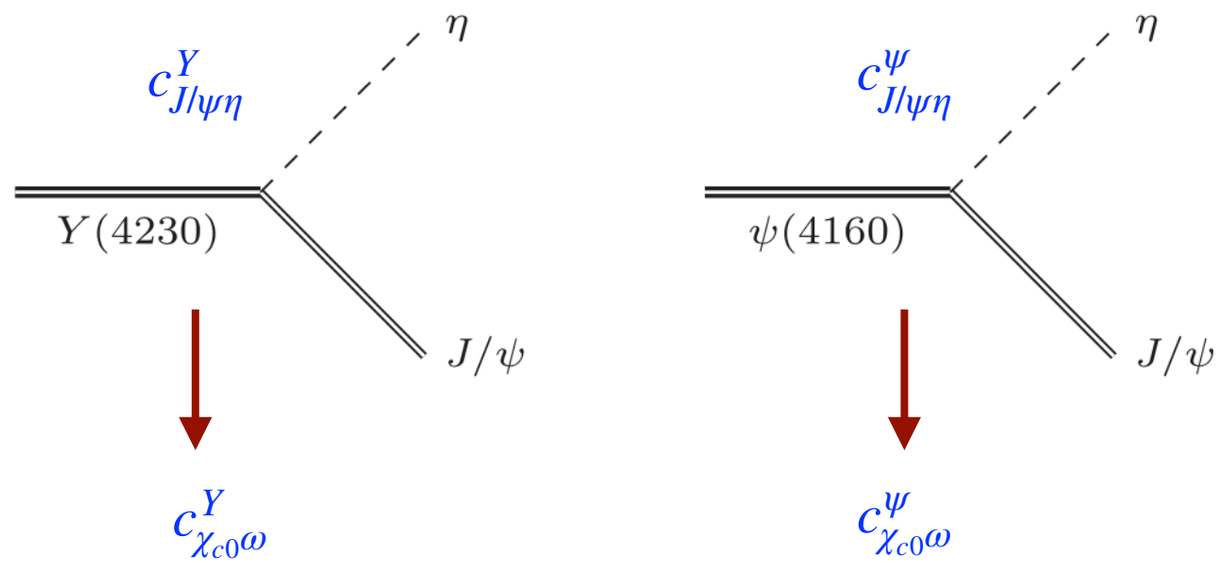


BESIII, PRL122(2019)232002



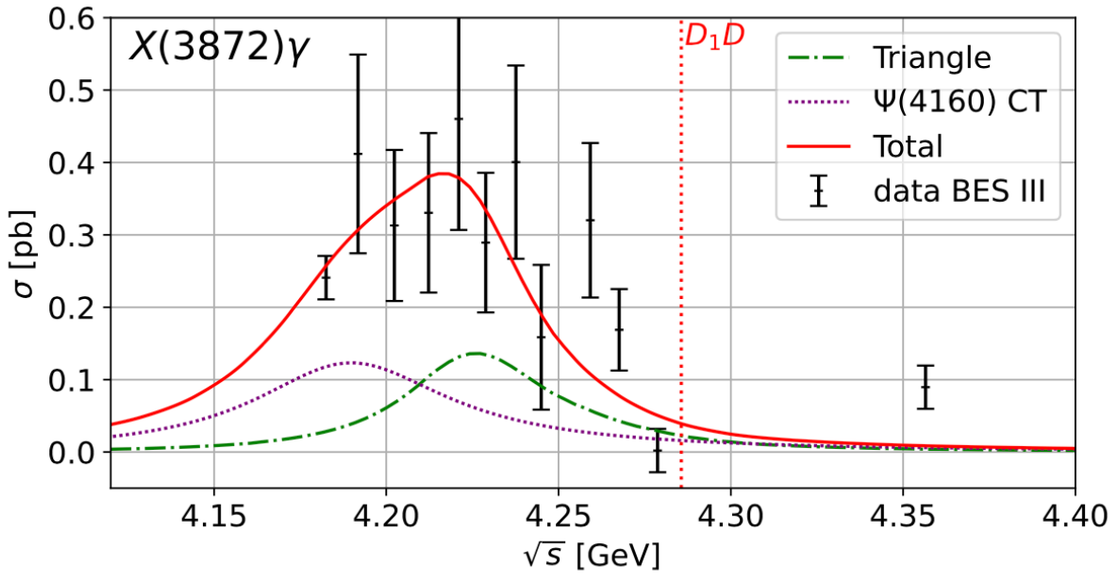
BESIII, PRD102(2020)031101



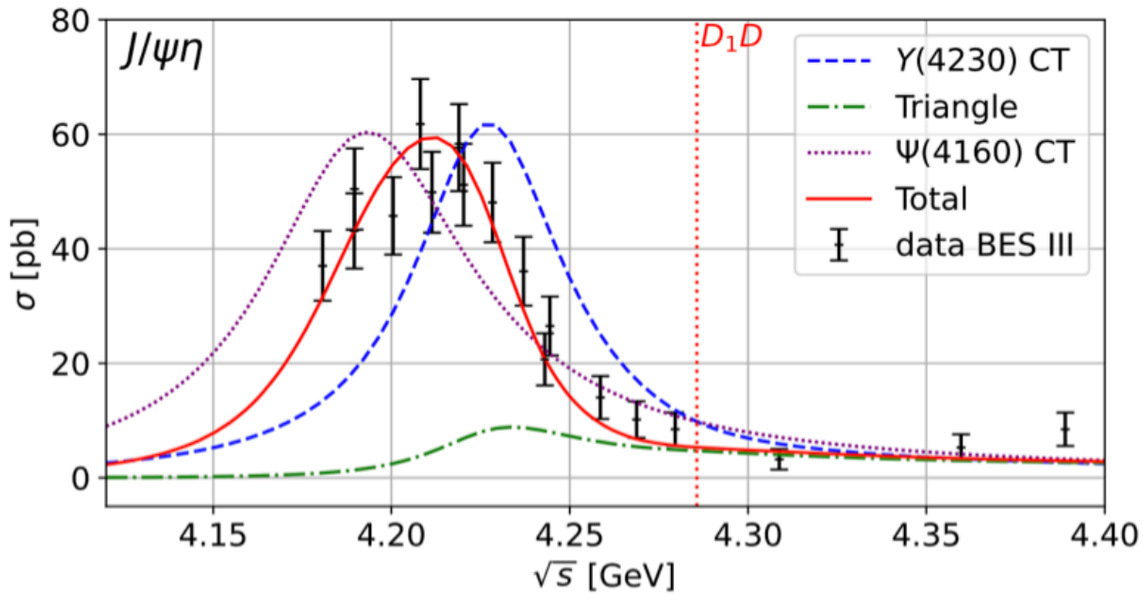


The $J/\psi\eta$, $\chi_{c0}\omega$, $X(3872)\gamma$ channels

- The $J/\psi\eta$, $\chi_{c0}\omega$, $X(3872)\gamma$ line shapes



BESIII, PRL122(2019)232002



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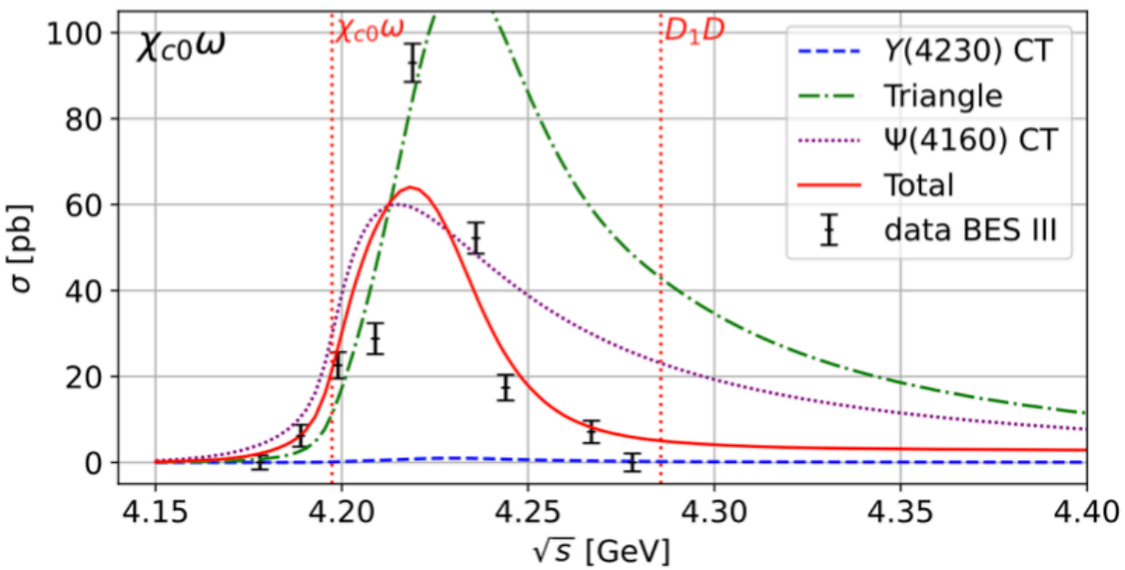


BESIII, PRD99(2019)091103

① Destructive in $\chi_{c0}\omega$

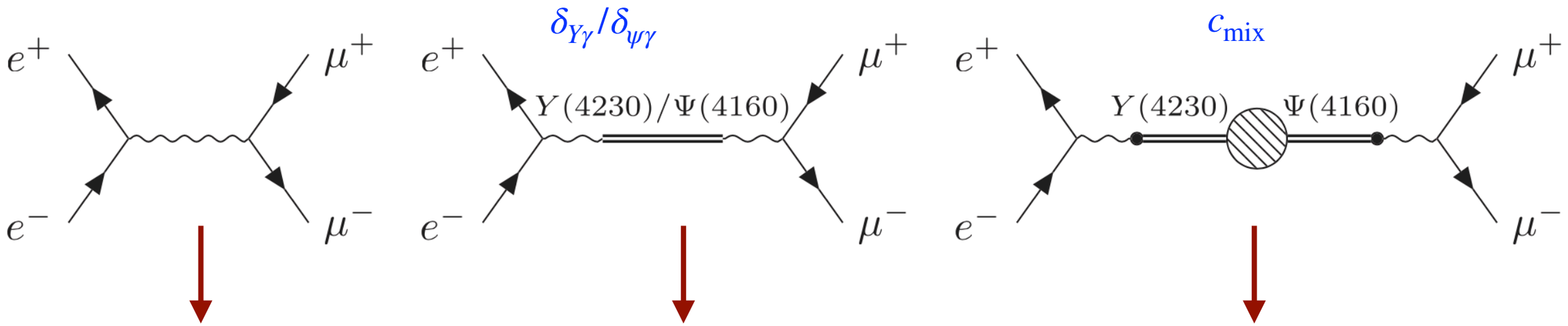
② Γ_ω is convoluted in $\chi_{c0}\omega$ channel

③ Constructive in $X(3872)\gamma$

④ Large statistic data is needed

The $\mu^+\mu^-$ channel

- $e^+e^- \to \mu^+ u^-$ process



$$\sigma^{\rm trree}_{e^+e^-\to\mu^+\mu^-} = \frac{4\pi\alpha^2}{3s} \qquad \mathscr{A}_R = \sum_{R=Y,\psi} g_{\gamma R} G_R g_{\gamma R} \qquad \mathscr{A}_{\rm mix} = \sum_{R\neq R'} g_{\gamma R} G_R \mathscr{M}^{RR'}_{\rm mix} G_{R'} g_{\gamma R'},$$

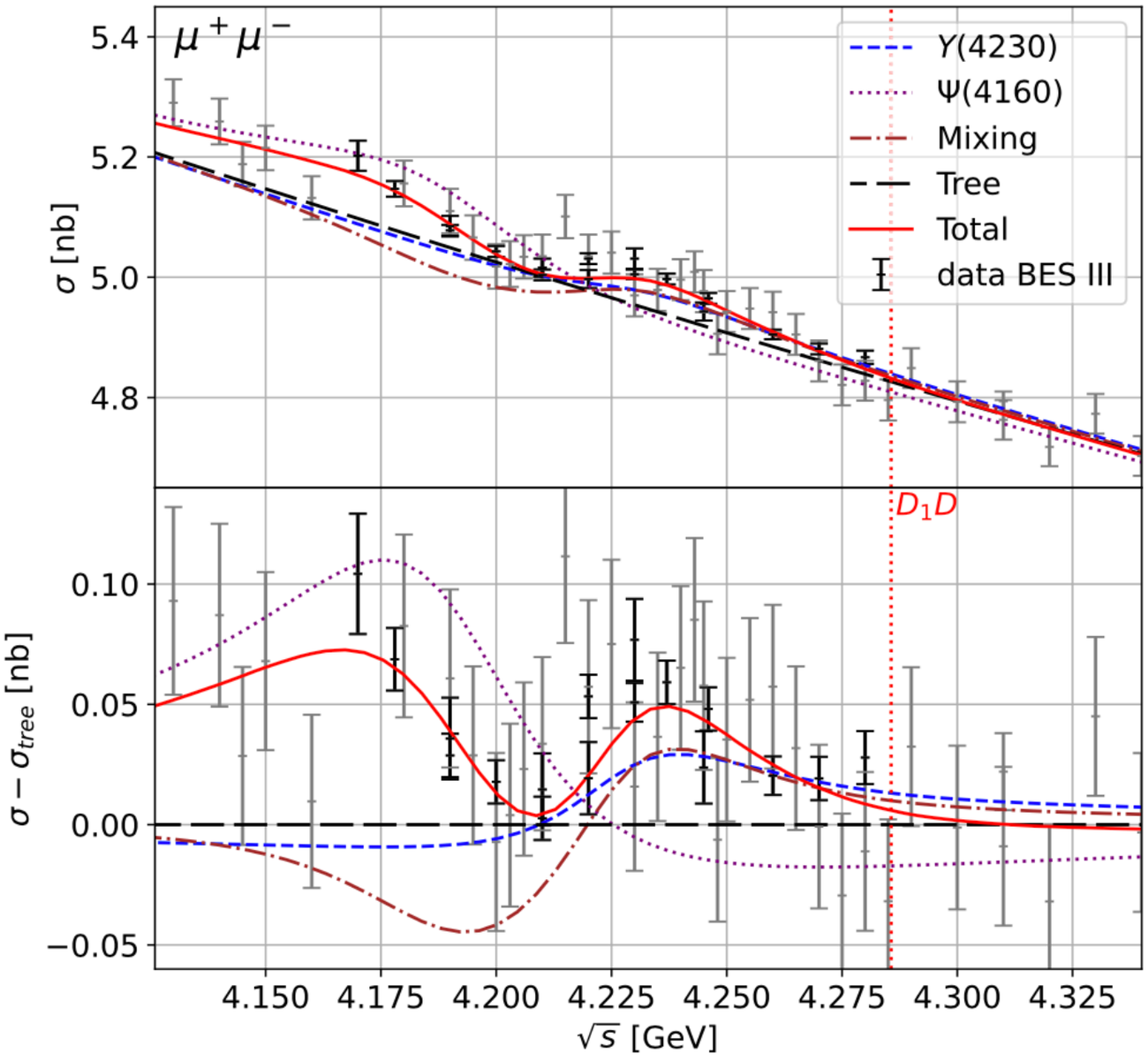
The cross section $\sigma_{e^+e^-\to\mu^+\mu^-} = \sigma^{\rm tree}_{e^+e^-\to\mu^+\mu^-} \left| 1 + \mathscr{A}_R + \mathscr{A}_{\rm mix} \right|^2$

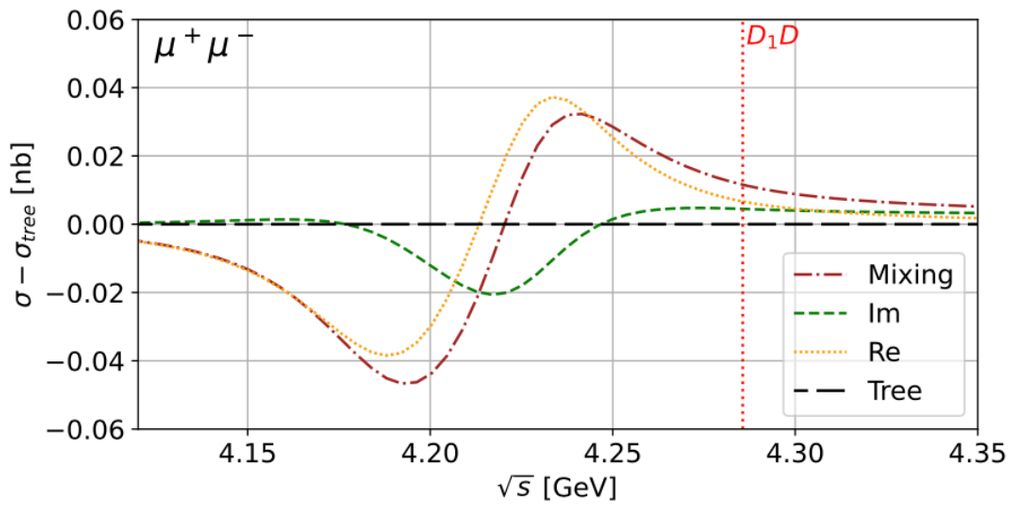
With tree-level cross section subtracted

$$\sigma_{e^+e^-\to\mu^+\mu^-} - \sigma^{\rm tree}_{e^+e^-\to\mu^+\mu^-} \approx 2\sigma^{\rm tree}_{e^+e^-\to\mu^+\mu^-} {\rm Re}\left(\mathscr{A}_R + \mathscr{A}_{\rm mix} \right).$$

The $\mu^+\mu^-$ channel

- The $e^+e^- \to \mu^+\mu^-$ cross sections





① Re changes the sign between the two states

② The dramatic changes of the cross section indicate the existence of the $\psi(4160)$

BESIII, PRD102(2020)112009

Summary and outlook

- A global fit to eight channels in a phenomenological way
- A combined fit of all channels require the presence of the $\psi(4160)$
- A single vector charmonium-like state $Y(4230)$ exits in [4.2, 4.35] GeV region
- $M^{\text{pole}}_{Y(4230)} = (4227 \pm 4) - i(25^{+4}_{-1})$ MeV, $M^{\text{pole}}_{Z_c(3900)} = 3884 - 22i$ MeV
- Asymmetric lineshape stems from the $D_1\bar{D}$ threshold

- A framework in EFT point of view
- Full $\pi\pi - K\bar{K}$ FSI

Thank you very much for your attention!