The nature of $Y(4260)$ and production of $Z_c(3900)$

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In collaboration with

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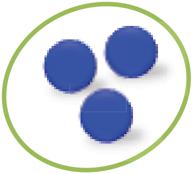
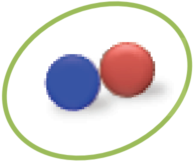
Outline

- A brief review of X, Y, Z particles
  - The theoretical aspect
  - The experimental aspect
- Some scenarios of $Y(4260)$
  - hybrid
  - hadro-charmonium
  - tetraquark
  - molecule
  - ...
- The molecular nature of $Y(4260)$ and its manifestation
  - The singularity region
  - The production of $Z_c(3900)$
  - The line shape of $Y(4260)$
- Summary and Outlook

Quark model predicts



Baryon, e.g. n, p

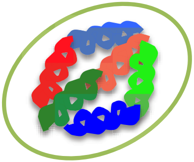


Meson, e.g. π, ρ

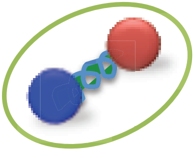
A brief review of X, Y, Z particles
The theoretical aspect

Other color singlet exotic configurations are also permitted by QCD:

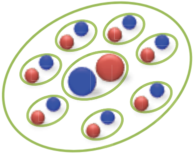
glueball



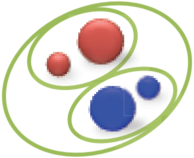
hybrid



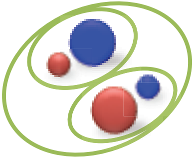
hadroquarknoium



tetraquark

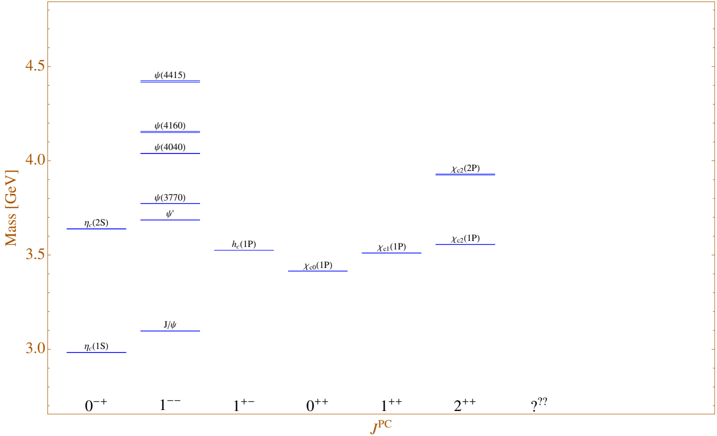


molecule



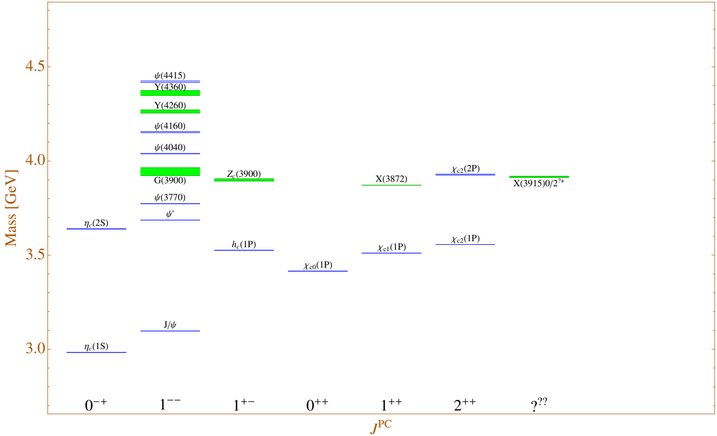
See talk by Feng-Kun Guo

Conventional charmonia



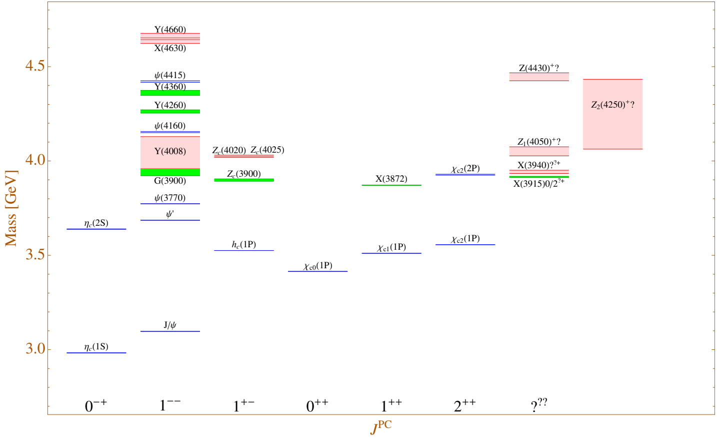
e^+e^- annihilation: BESIII, Belle, CLEO, BABAR; B decay: Belle, BABAR; Hadron collider: Tevatron, LHC

Well-established exotic states



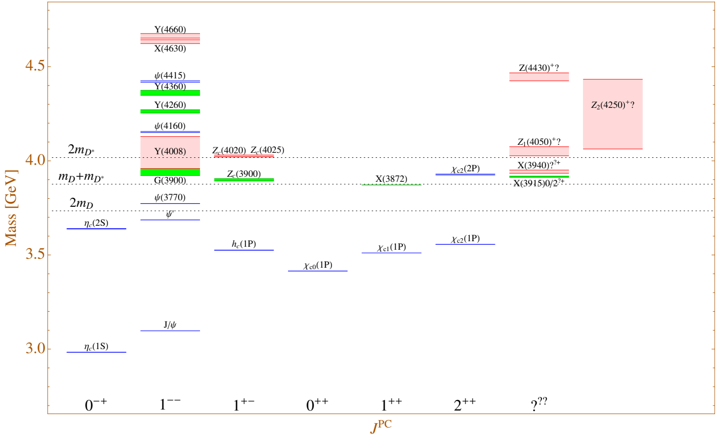
e^+e^- annihilation: BESIII, Belle, CLEO, BABAR; B decay: Belle, BABAR; Hadron collider: Tevatron, LHC

Some unconfirmed exotic states



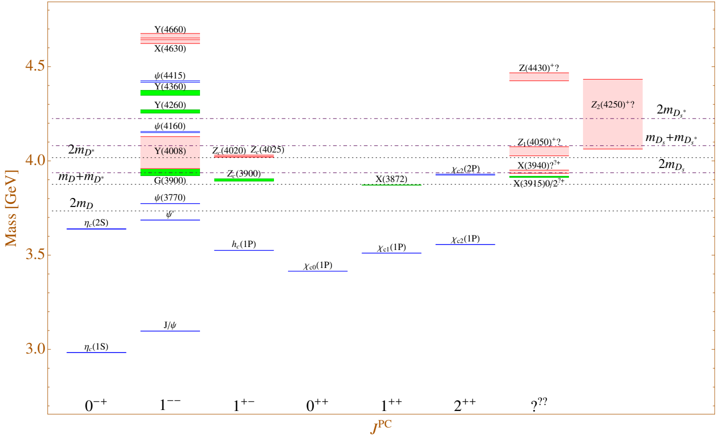
e^+e^- annihilation: BESIII, Belle, CLEO, BABAR; B decay: Belle, BABAR; Hadron collider: Tevatron, LHC

The DD, DD^*, D^*D^* thresholds



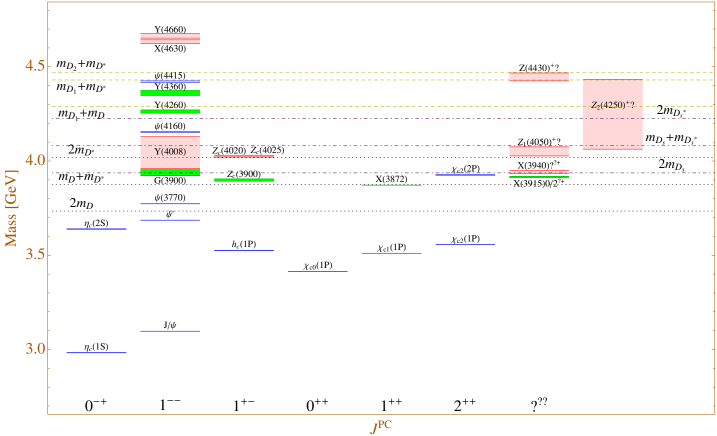
e^+e^- annihilation: BESIII, Belle, CLEO, BABAR; B decay: Belle, BABAR; Hadron collider: Tevatron, LHC

The D_sD_s, $D_sD_s^*$, $D_s^*D_s^*$ thresholds



e^+e^- annihilation: BESIII, Belle, CLEO, BABAR; B decay: Belle, BABAR; Hadron collider: Tevatron, LHC

The $D_1 D$, $D_1 D^*$, $D_2 D^*$ thresholds



e^+e^- annihilation: BESIII, Belle, CLEO, BABAR; B decay: Belle, BABAR; Hadron collider: Tevatron, LHC

Figure : The $\Upsilon(nS)\pi$ invariant mass in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ processes.

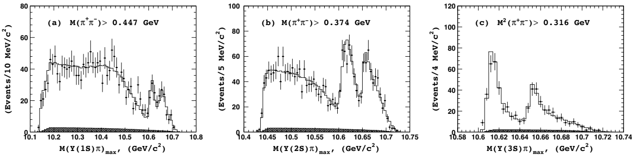
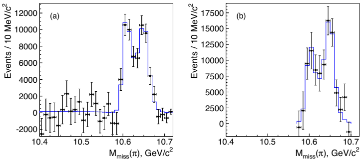


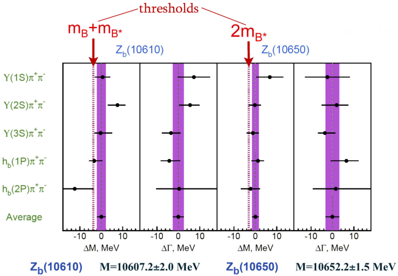
Figure : The missing pion mass distribution in $\Upsilon(5S) \to h_b(mP)\pi\pi$ processes.



Belle, Phys.Rev.Lett. 108, 122001(2012); Belle, hep-ex/1209.6450(2012), talk by Cheng-ping Shen.

A brief review of X, Y, Z particles

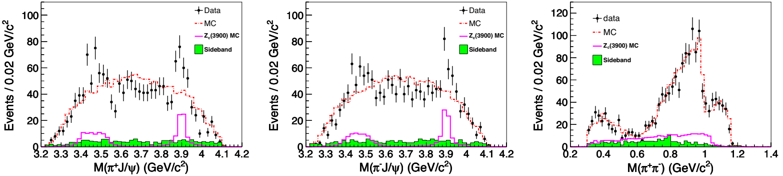
$Z_b(10610)$ and $Z_b(10650)$



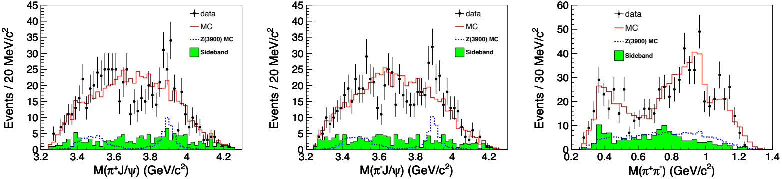
Branching ratio (%)	$Z_b(10610)$	$Z_b'(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.82 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	—
$B^{*+}\bar{B}^{*0}$	—	73.4 ± 7.0

Belle, Phys.Rev.Lett. 108, 122001(2012); Belle, hep-ex/1209.6450(2012); M.Cleven et al, Phys.Rev.D87, 074006(2013); talk given by W.Wang on QWG2013

Consistent with each other!



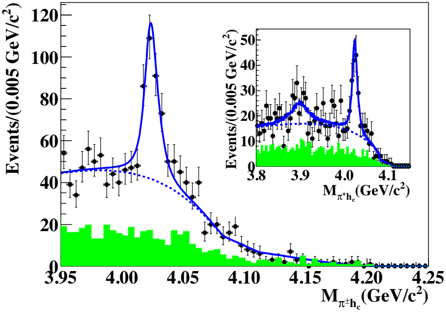
$$M = 3899.0 \pm 3.6 \pm 4.9\ \mathrm{MeV}, \quad \Gamma = 46 \pm 10 \pm 20\ \mathrm{MeV}$$

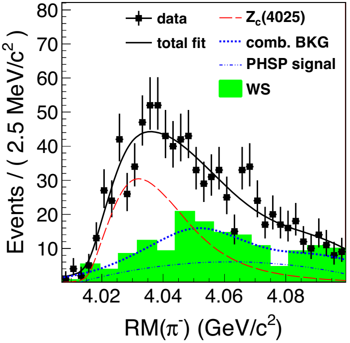


$$M = 3894.5 \pm 6.6 \pm 4.5\ \mathrm{MeV}, \quad \Gamma = 63 \pm 24 \pm 26\ \mathrm{MeV}$$

BESIII, Phys.Rev.Lett., 110, 252001(2013); Belle, Phys.Rev.Lett., 110, 252002(2013); See talk by Zhi-qing Liu.

One state or two states?





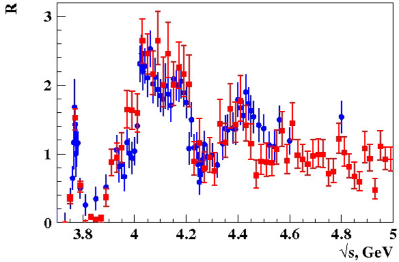
$$m_{Z_c(4020)} = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}$$
$$\Gamma_{Z_c(4020)} = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$

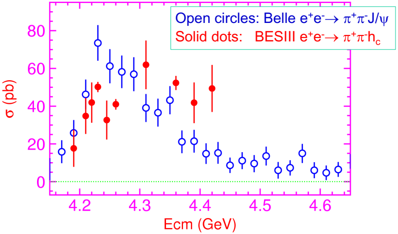
$$m_{Z_c(4025)} = 4026.3 \pm 2.6 \pm 3.1 \text{ MeV}$$
$$\Gamma_{Z_c(4025)} = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$$

BESIII, hep-ex/1309.1896(2013); BESIII, hep-ex/1308.2760(2013); See talks by Xiao-Rui Lu and Yu-ping Guo.

No signals in both R-Value measurement and open charmed channels.

Only well established in $J/\psi\pi\pi$ channel and some hint in $h_c\pi\pi$ channel.



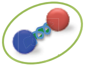


Talk given by Galina Pakhlova on QWG 2011; Talk given by Chang-zheng Yuan on Charm 2013; BESIII arXiv:1309.1896 [hep-ex].

Some scenarios of $Y(4260)$

Configurations, dominant decay modes and behaviours in e^+e^- annihilation

hybrid



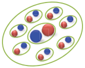
$(c\bar{c})_{0^{-+}} + g_{1^{+-}}$

η_c+light mesons

suppressed

S. -L. Zhu, Phys. Lett. B **625**, 212 (2005); E. Kou and O. Pene, Phys. Lett. B **631**, 164 (2005); F. E. Close and P. R. Page, Phys. Lett. B **628**, 215 (2005), talk by Ying Chen.

hadro-charmonium



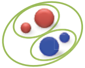
$(c\bar{c})_{1^{--}}$+light mesons

$J/\psi + 2\pi$

enhanced

M. B. Voloshin, Phys. Rev. D **87**, 091501 (2013), N. Mahajan, arXiv:1304.1301 [hep-ph].

tetraquark



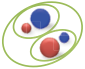
$([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{P-wave}$

$D_s^*\bar{D}_s^*$

suppressed

L. Maiani, V. Riquer, F. Piccinini and A. D. Polosa, Phys. Rev. D **72**, 031502 (2005), talk by Ting-Wai Chiu.

molecule



$D_1\bar{D} - \bar{D}_1 D$

$D\bar{D}^*\pi + c.c.$

suppressed

Q. Wang, C. Hanhart and Q. Zhao, Phys. Rev. Lett. **111**, 132003 (2013), G. -J. Ding, Phys. Rev. D **79**, 014001 (2009).

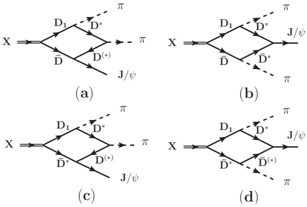
No matter what natures they are, the threshold effect does exist!

We use the lagrangians below to express the incoming vector meson coupling to $D_1 D$ and $D_1 D^*$

$$\mathcal{L}_Y = iy(D_a^\dagger Y^i \bar{D}_{1a}^{\dagger i} - D_{1a}^{\dagger i} Y^i \bar{D}_a^\dagger) + y\epsilon^{ijk}(D_{1a}^{\dagger i} Y^k \bar{D}_a^{*\dagger j} - D_a^{*\dagger j} Y^k \bar{D}_{1a}^{\dagger i}) + H.c.$$

and the narrow D_1 decay to $D^*\pi$.

$$\mathcal{L}_{D_1} = i\frac{h'}{f_\pi}[3D_{1a}^i(\partial^i\partial^j\phi_{ab})D_b^{*\dagger j} - D_{1a}^i(\partial^j\partial^j\phi_{ab})D_b^{*\dagger i} + 3\bar{D}_a^{*\dagger i}(\partial^i\partial^j\phi_{ab})\bar{D}_{1b}^j - \bar{D}_a^{*\dagger i}(\partial^j\partial^j\phi_{ab})\bar{D}_{1b}^i] + H.c$$



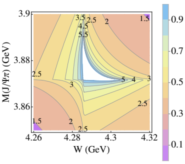
Since the charmed meson exchanged between J/ψ and π is far off-shell, the amplitude can be analyzed as

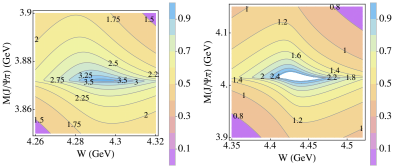
$$\mathcal{M} = \int \frac{d^4 l}{(2\pi)^4} \frac{G\epsilon_X^i \epsilon_{J/\psi}^j (3q_1^i q_1^j - |q_1|^2\delta^{ij})\mathcal{F}(M(J/\psi\pi), t)}{(l^0 - \frac{|\vec{l}|^2}{2m_{D_1}} + i\varepsilon)(p^0 - l^0 - \frac{|\vec{l}|^2}{2m_{D^{(*)}}} + i\varepsilon)(l^0 - q_1^0 - \frac{|\vec{l}-\vec{q_1}|}{2m_{D^*}} + i\varepsilon)}$$

$$\equiv G\epsilon_X^i \epsilon_{J/\psi}^j (3q_1^i q_1^j - |q_1|^2\delta^{ij})\mathcal{F}(M(J/\psi\pi), t)\mathrm{I}(m_{D_1}, m_{D^{(*)}}, m_{D^*}, W, M(J/\psi\pi), m_\pi),$$

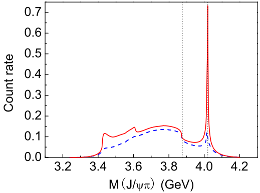
Q. Wang, C. Hanhart and Q. Zhao, Phys. Lett. B **725**, (2013)

The singularity region

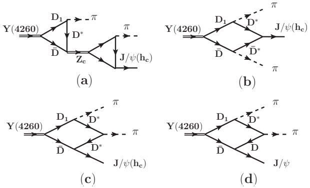


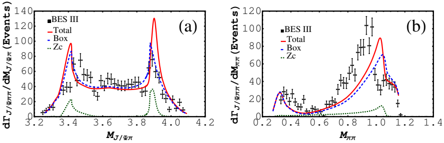


The corresponding line shape at the centre energy 4.43 GeV



$Y(4260)$ lies in DD^* singularity region:





- The large production rate of DD^* at 4.26 GeV since it lies in the DD^* singularity region
- Box diagrams provides most of back ground contributions
- The dip at about 1 GeV is shifted above $K\bar{K}$ threshold due to other higher partial waves' contribution
- The explicit inclusion of $Z_c(3900)$ pole contribution makes the structure at DD^* threshold broader
- $Y(4260)$ should be dominated by $D_1 D$ component
- $DD^* \pi$ is the dominate decay mode and the line shape of $Y(4260)$ is largely affected by the nearby $D_1 D$ threshold

Q. Wang, C. Hanhart and Q. Zhao, Phys. Rev. Lett. **111**, 132003 (2013)

The line shape of $Y(4260)$

The propagator of $Y(4260)$ can be expressed as

$$G_Y(s) \quad = \quad (s - M_0^2 + g_0^2\Pi(s))^{-1} = Z(s - {M_Y}^2 + g^2\hat{\Pi}(s))^{-1}, \tag{1}$$

where the mass position is defined as

$$M_Y^2 - M_0^2 + g_0^2 Re[\Pi(M_Y^2)] = 0 \tag{2}$$

and

$$\hat{\Pi}(s) \quad = \quad \Pi(s) - \mathrm{Re}\left[\Pi(M_Y^2) + (s - M_Y^2)\partial_s\Pi(s)|_{s=M_Y^2}\right].$$

Here $Z = (1 - Re[\Pi'(M_Y^2)])^{-1}$ is the renormalized constant and $g^2 = g_0^2 Z = \frac{16\pi}{\mu}\sqrt{\frac{2\epsilon}{\mu}}$ is the physical coupling constant. To take into account the other possible decay modes without through $D_1 D$ component, a constant width Γ_Y is added to the propagator. So the full propagator is

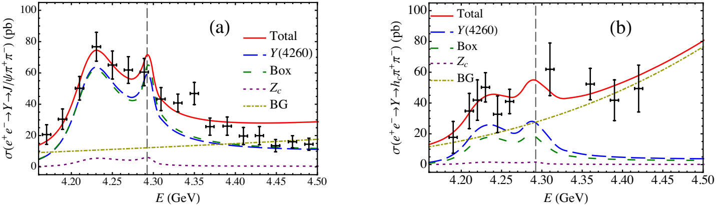
$$G_Y(s) \quad = \quad \left[s - M_Y^2 + g^2\hat{\Pi}(s) + iM_Y\Gamma_Y\right]^{-1}.$$

The cross section of the full process $e^+e^- \to Y \to f$ can be expressed as

$$\sigma(s) = (4\pi\alpha)^2\left(g_{\gamma^*Y}\frac{M_Y^2}{s}\right)^2(M_Y\Gamma_{Y\to f})|G_Y(s)|^2. \tag{3}$$

M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meißner and Q. Zhao, arXiv:1310.2190 [hep-ph].

To get the mass position of $Y(4260)$, we fit its line shape in $J/\psi\pi\pi$ and $h_c\pi\pi$ channels. The fitted results are $M_Y = (4220 \pm 5)$ MeV and $\Gamma_Y = (40 \pm 9)$ MeV. The corresponding line shapes are as below



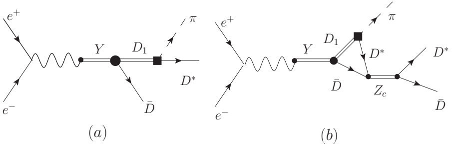
M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meißner and Q. Zhao, arXiv:1310.2190 [hep-ph].

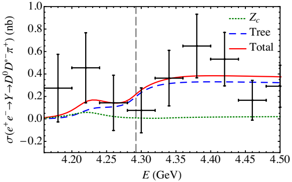
The molecular nature of $Y(4260)$ and its manifestation

The line shape of $Y(4260)$

$e^+e^- \to Y(4260) \to DD^*\pi$

Feynman Diagrams

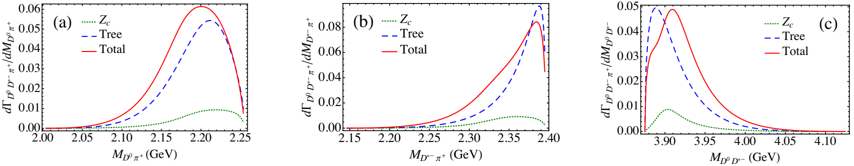




- The nontrivial structures of the line shape of $Y(4260)$ at the $D_1 D$ threshold in the $J/\psi\pi\pi$, $h_c\pi\pi$ channels can be viewed as an evidence that $Y(4260)$ is dominated by the $D_1 D$ component.
- The threshold effect in $DD^*\pi$ channel is not as significant as that in the $J/\psi\pi\pi$ and $h_c\pi\pi$ channels since it is dominated by the tree diagram.
- The fitted mass of $Y(4260)$ is (4220 ± 5) MeV which is a little lower than the PDG averaged value.
- That the constant width is smaller than half of the total width is an evidence that $Y(4260)$ is dominated by $D_1 D$.

M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meißner and Q. Zhao, arXiv:1310.2190 [hep-ph].

The $D\pi$, $D^*\pi$ and DD^* invariant mass distributions

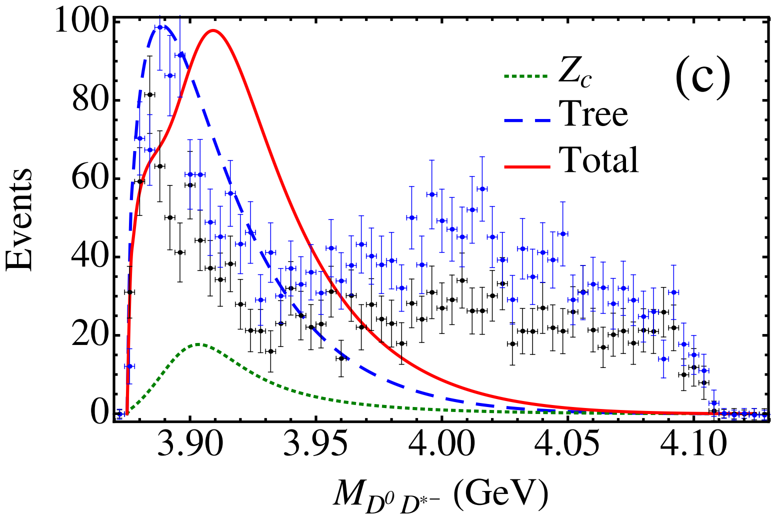


- The D_1 pole contribution in $D^*\pi$ invariant mass can be viewed as another evidence that $Y(4260)$ is $D_1 D$ molecule.
- The enhancement at higher mass in $D\pi$ invariant mass are due to the relative D-wave behavior of $D^*\pi$ in D_1 decay.
- The enhancement at lower mass of DD^* is due to the relative S-wave behavior

M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meißner and Q. Zhao, arXiv:1310.2190 [hep-ph],

X. -H. Liu and G. Li, Phys. Rev. D **88**, 014013 (2013).

DD^* invariant distribution compare to experiment



See talks by Xin-Ping Xu and Xiao-Rui Lu.

Summary and Outlook

- $Y(4260)$ is dominated by $D_1 D$ component and its dominant decay mode should be $DD^*\pi$.
- The line shape of $Y(4260)$ is largely dependent on the nearby $D_1 D$ threshold in the $J/\psi\pi\pi$ and $h_c\pi\pi$ channels.
- The fitted mass is (4220 ± 5) MeV which is a little lower than the PDG average.
- Further measurements in $\eta_c +$ light mesons and $D_s^* D_s^*$ channels are necessary to probe $Y(4260)$'s nature.
- D_1 pole contribution in $D^*\pi$ invariant mass can be viewed as evidence for $Y(4260)$'s being as a $D_1 D$ molecule.
- The combination of the light degrees of freedom $(\frac{3}{2})^+$ and $(\frac{1}{2})^-$ can not give 0 which makes the production of $Y(4260)$ is suppressed in e^+e^- annihilation.
- The observation of $Z_c(3900)$ is a natural result of $Y(4260)$'s molecular nature.
- Further scans at different c.m. energies especially out of the singularity region are necessary to determine whether $Z_c(3900)$ is a genuine state or not.

Thanks for your attention

BackUp